Water and nutrient dynamics of Pinus caribaea plantation forests on former grassland soils in Southwest Viti Levu, Fiji

Waterloo, M.J.

1994

Water and Nutrient Dynamics of *Pinus caribaea* Plantation Forests on Former Grassland Soils in Southwest Viti Levu, Fiji

Maarten J. Waterloo

May 1994, updated and converted to PDF document in August 2002

Contents

Part I

Background Information and Introductory Chapters

Chapter 1

Introduction

To meet rising demands for timber, pulp and land for various agricultural purposes, tropical moist forests are being cleared at an ever increasing rate (Lanly *et al.*, 1991) The causes of tropical forest decline vary between continents and regions (Whitmore, 1990). However, contrary to the general public belief uncontrolled slash and burn agriculture (either before but usually after an area has been opened up by loggers) rather than logging *per sé* must be considered the prime factor in this respect. If an area becomes subjected to fire too frequently for the vegetation to regenerate properly, the land generally becomes covered with relatively unproductive scrub or grassland (Jordan, 1987; Mueller-Dombois and Goldammer, 1990). In other areas such as the Amazon Basin, vast tracks of forests have been converted to ranchland, often with disastrous results, particularly when clearing was effected with the help of heavy machinery compacting the soil (Uhl *et al.*, 1982). Again the frequent use of fire to suppress regenerating vegetation in such areas has not only diminished chances for a successful return of the original forest (Buschbacher, 1986; Uhl *et al.*, 1988) but has also left large areas of largely unproductive wasteland. Such degraded areas are becoming more and more important for the establishment of fast-growing plantation forests, as a viable alternative source of wood (Evans, 1992). However, little is known yet about the potentially negative impact of afforestation of such areas on water yield and quality (Bruijnzeel, 1990). Furthermore, the question arises as to how long wood production can be sustained without the application of fertilizers, particularly in the case of fast-growing exotic species planted on already depleted degraded soils (Bruijnzeel, 1992b; Evans, 1992). Both problems have become particularly manifest in the dry leeward zone of Viti Levu, a 10,497 km^2 island within the Fiji group in the SW Pacific.

The dry side of Viti Levu was deforested during the previous century as a result of slash and burn agriculture by the Fijians and the introduction of grazing on a larger scale after the coming of European settlers. Grazing and repeated burning of the regenerating vegetation resulted in a well-established, fire climax grassland vegetation (Drysdale and Rawaqa, 1987). The dominant grassland species (*Pennisetum polystachyon*) is not indigenous and was imported by accident at the beginning of this century. In the 1950s plans were developed to establish exotic plantation forests on these grasslands for the following reasons (Fiji Times Timber Industry Supplement, 1990):

- Plantation species provide more wood per unit surface area and take shorter time to mature than indigenous forests

- Plantation forests form a ready source of timber and may serve to protect the land from erosion
- Land that would normally be idle becomes utilized
- Plantation forests form a future source of money, and create bussiness opportunities and employment for the land owners[1].

Following trials with various tree species on the grassland soils *Pinus caribaea* was selected. In 1976, the Fiji Pine Commission was formed with the objective of establishing a viable forest industry based on planted species, of which the management and ownership would eventually be transferred to the native landowners. Since then a total of 23,230 ha of grassland has been converted to pine plantation forest in West Viti Levu (Yabaki, 1991). The Fiji Pine Commission was privatized in 1991 and the newly formed enterprise Fiji Pine Limited took over all the assets, liabilities and obligations.

Urban water supplies in Viti Levu, Fiji, depend mainly on surface water, derived from catchments in the interior of the island. In the late 1960s and early 1970s the grassland vegetation in several of the water supply catchments (*e.g.* Nawetavuni, Varaciva catchments) for the Ba Province was converted to pine plantation forest. However, several years after the conversion water shortages started to develop during the dry season, which were attributed to differences in water use between the pine forests and the grassland vegetation (Kammer and Raj, 1979). Planting activities of the Fiji Pine Commission are restricted to the dry western parts of Viti Levu and Vanua Levu and widespread reforestation of these dry grassland areas could therefore result in serious local water supply problems. Large-scale planting of trees has only begun recently in tropical countries (Evans, 1992) and information on the water use of either tropical grasslands or *Pinus caribaea* plantation forests, and therefore on effects of afforestation on water yield, was not available elsewhere. As such there was a need to quantify the water use of both vegetation types to enable the calculation of the economic implications of reforestation in Viti Levu, relative to the increased costs of water supply. The emphasis of such a study should be on dry season water use, as water yield during the rainy season was sufficient to meet the demands (Drysdale and Rawaqa, 1987).

The forests in the water supply catchments of the Ba Province were logged during the late 1980s. This was followed by a general decrease of the water quality (high sediment load, discolorisation) and amounts of sediment in streamflow during larger storms were such that water intake had to be stopped due to clogging of the filters at the intake stations, leaving the residents of Ba town without water. Extra filters needed to be installed in the early 1990's to meet the demand for water during the wet season.

In addition to the question of increased water use by plantation forests and the negative effects of harvesting on water quality, concern has been expressed that the establishment of fast-growing trees on degraded soils may deplete soil nutrient reserves, resulting in low wood production during subsequent rotations. In Fiji, the production of second rotation forests fell below that of the first-rotation forests. It was not clear at the time whether this decline in productivity was related to water shortage during the dry season, to nutrient deficiencies, or frequent disturbance of the stands by cyclones. Indeed, at some locations signs of nutrient deficiencies (*e.g.* shoots without

[1]In Fiji most land is communal property and the land owners are indigenous Fijians who belong to the *Mataqali* (clan) which has communal rights over the area

needles) were observed in second rotation forests (Dr. J.H.R. Heuch, pers. comm.). Although these deficiencies could possibly be overcome by fertilizing, the application of fertilizers to extensive forest areas would increase the costs of plantation development considerably. As such the sustainability of the current management practice needed to be evaluated to provide quantitative data on which predictions of the future costs of reforestation could be based.

A project was initiated in 1989 to address the pressing issues formulated above. The project was a collaboration of the Netherlands Foundation for the Advancement of Tropical Research (WOTRO, grant no. W84-295), the Faculty of Earth Sciences from the Vrije Universiteit of Amsterdam (FES-VUA) and the then Fiji Pine Commission (FPC). The work was undertaken by the author in partial fulfillment of the requirements of a doctoral degree from VUA, by his counterpart Mr. T.T. Rawaqa from the then FPC, and by seven FES-VUA students in fulfillment of the requirements for their MSc degree. Field research was carried out over a two year period with the following objectives:

- To quantify the dry season water use of grassland, and that of a chronosequence of *Pinus caribaea* plantation forests planted on comparable soils
- To quantify the various components of the water and nutrient cycles over the period of a rotation (typically 15–20 years in the area)
- To study the effect of mechanized harvesting of merchantable timber, and subsequent burning of the slash on water yield and quality, as well as on soil properties
- To test various techniques that have become widely used in temperate zone forest hydrological research under humid tropical conditions
- To integrate the results in a descriptive mathematical model capable of making extrapolations in time

As it was not feasible to monitor a single forest over the length of a rotation the 'false time series' approach (Hase and Fölster, 1982; Bruijnzeel, 1983a) was used. The underlying assumption is that changes in water use and nutrient cycling following the planting of pines on grasslands, and those occurring over a rotation period, can be simulated by studying a forest age sequence provided that the environmental conditions (*e.g.* climate, topography, soil physical and chemical properties) in the study areas are similar.

Three levels of cycling can be recognised (Miller, 1984). The largest cycle is that which links the ecosystem to the global ecosystem by exchanges of energy, solids, liquids and gasses through the ecosystem boundaries. The second cycle represents cycling within the ecosystem boundaries (soil – vegetation system), whereas the third cycle concerns the retranslocation of nutrients and water within the vegetation. The relocation of nutrients within the ecosystem boundaries has been referred to as the intra-system cycle (Likens *et al.*, 1977).

The various pathways of water through a forest ecosystem are shown in a schematic diagram (Figure 1.1). Proctor (1987) described the major nutrient pathways linking the various storage pools as follows:

> *Nutrients enter the ecosystem with the rain, deposition of dust and aerosols, (in the case of nitrogen) by fixation of micro-organisms above and below ground, and (except for nitrogen) by weathering of the underlying rock. The major above-ground pool of nutrients is the canopy (defined as the total plant community) and there is a flow of nutrients from this to the*

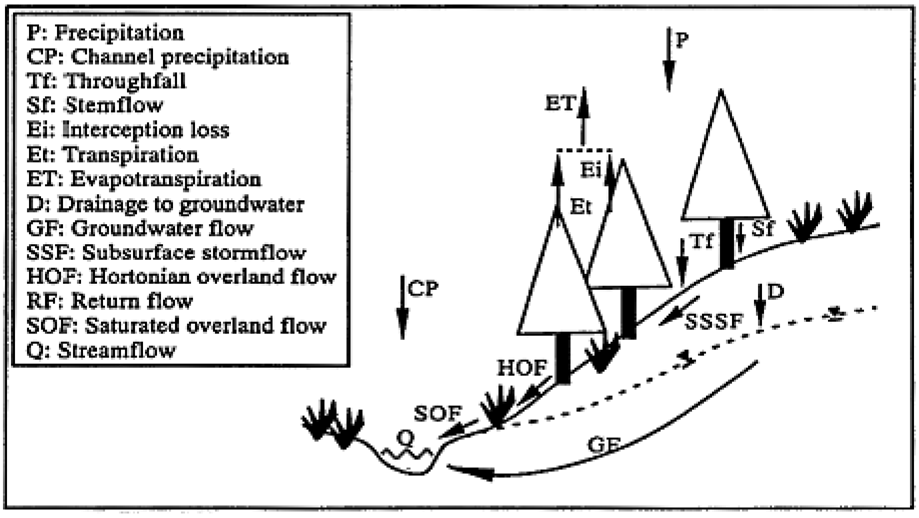


Figure 1.1: *Schematic drawing showing the major components of the hydrological cycle for a pine forest ecosystem.*

> *forest floor in small and large litterfall and in throughfall and stemflow of rainwater, which usually becomes enriched by nutrient from leaves and bark. A proportion of the above-ground nutrients is in dead organic matter such as standing dead trees and small and large litter lying on the forest floor. Nutrients are gradually released from the dead matter by decomposition mediated by soil animals and micro-organisms. Decomposition is complex and can involve immobilization of nutrients as well as their release. Nutrients are taken up from the exchange complexes of the soil by roots (probably usually in association with mycorrhizal fungi) which provide a living below-ground pool and which export them to the canopy. The roots release nutrients to the soil as secretions and by the death and decomposition of their parts. Permanent loss of nutrients occurs through surface erosion, fires, loss in drainage water and in the case of nitrogen by abiotic or microbial denitrification. Some, particularly phosphorus, may effectively leave the system by conversion into insoluble inorganic forms within the soil.*

A schematic drawing of the major pathways of nutrients fluxes both in water and as solids (gaseous phase excluded), as well as their sources and sinks in a forested ecosystem is shown in Figure 1.2.

Baillie (1989) distinguished two types of nutrient cycles, *viz.* open and closed. In the former, nutrients are provided to the ecosystem by both atmospheric sources and weathering of the soil–rock system, whereas in closed cycles the ecosystem is sustained entirely by atmospheric inputs and internal cycling of nutrients. Nutrient losses from ecosystems with closed cycles therefore largely reflect atmospheric inputs, whereas those from ecosystems with open cycles are higher, reflecting additional losses by weathering. Repeated removal of biomass and associated nutrients from a 'closed' ecosystem will in the end result in a depletion of the soil nutrient reserves.

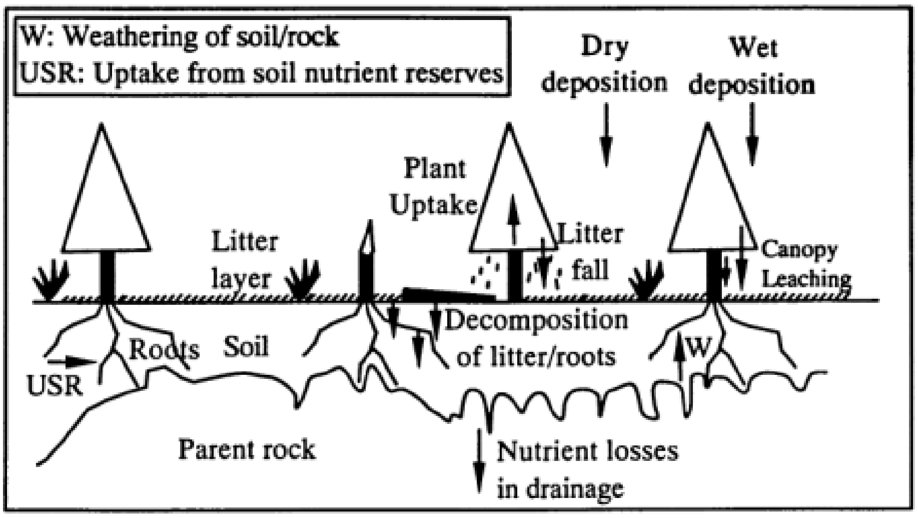


Figure 1.2: *Schematic drawing depicting the various sources, sinks and pathways of nutrients through a forest ecosystem. Modified after Proctor (1987).*

The systems approach of Likens *et al.* (1977) is used in the following chapters to describe the flow of water, nutrients and energy in the ecosystems under consideration.

Fiji lies in the area frequently traversed by tropical cyclones, and the passage of cyclone Sina one year after the initiation of the project provided a unique opportunity to study the effects of cyclone damage (*e.g.* large-scale defoliation) on the water and nutrient fluxes through the forest ecosystem using the data collected in the pre-cyclone period as a reference.

This thesis is divided into five parts. Part I contains various types of background information including soil physical and chemical characteristics. The various components of the water cycles in the forest ecosystems and the water use of grassland and pine forest as determined by various hydrological and micro-meteorological techniques are quantified in Part II. A discussion of the impact of afforestation on water yield is given at the end of Part II in Chapter 9. The nutrient cycles of the grass and forest plots are described in Part III and a sumarizing discussion of is given in Chapter 14. The impact of logging and subsequent burning of slash on water quantity and quality, as well as on the litter layer and soil, containing some of the original data sets, are treated in Part IV. Finally, conclusions, recommendations, summaries and acknowledgements are given in Part V, whereas the bibliography and various appendices make up Part VI. Each chapter starts with a short introduction, in which the literature relevant to the subject is discussed.

Chapter 2

General Information

2.1 Research Location and Physiography

The Fiji archipelago is situated in the Pacific Ocean between 16°S, 177°E and 20°S and 178°30'W. One island (Ceva-i-ra, 21°40'S, 174°40'E) and a small island group (Rotuma, 12°30'S, 177°E) belong to the country but fall outside the archipelago. The group consists of over 300 islands and reefs of which Viti Levu is the largest with an area of 10,497 km^2 (Ladd, 1934). Most of the islands are of volcanic origin.

The topography of the larger islands of Viti Levu, Vanua Levu and Taveuni is rather pronounced, with mountain heights between 900 and 1320 m a.s.l. Viti Levu consists for some 67% of steepland with slopes of 18–70° (Morrison and Clarke, 1990). There are several mountain ranges on the island, with altitudes of individual mountains varying between 500 and 1323 m a.s.l. (Figure 2.1). The largest mountain chain consists of several ranges (Tikituru, Nakauvadra) and high plateaus (Nadrau, Rairaimatuku) aligned in a SSW–NNE direction. This chain stretches from the south coast (Tuvutau, 933 m a.s.l.) to the north coast (Uluda, 866 m a.s.l.) and includes the highest mountain within the Fiji group. The mountains are bordered by strongly dissected plateaus and plains with elevations varying between 100 and 500 m a.s.l.

Some 15% of Viti Levu consists of flat lands (Morrison and Clarke, 1990). These are found along most of the coast and in the river valleys and flood plains of the four major rivers. The Rewa river in East Viti Levu is the largest, draining nearly one third of the island. The second largest river is the Sigatoka river, which drains the southeastern part of the island, followed by the Ba river draining the northeastern part. The Navua system is the smallest and drains the southern part of Viti Levu. The drainage pattern tends to be rectangular, possibly as a consequence of block faulting (Ladd, 1934).

Five pine forest estates have been established by the Fiji Pine Ltd., four of which are situated in the dry zone of Viti Levu (Figure 2.1), and the other in the dry zone of Vanua Levu (Bua Forest Estate).

The present study was conducted in the Nabou Forest Estate in the Nadroga district, SW Viti Levu, about 25 km south of Nadi and 20 km northwest of Sigatoka. The location of the study sites within the Nabou Forest estate are shown in Figure 2.2.

The estate is steeply dissected and elevations range from just above sealevel near

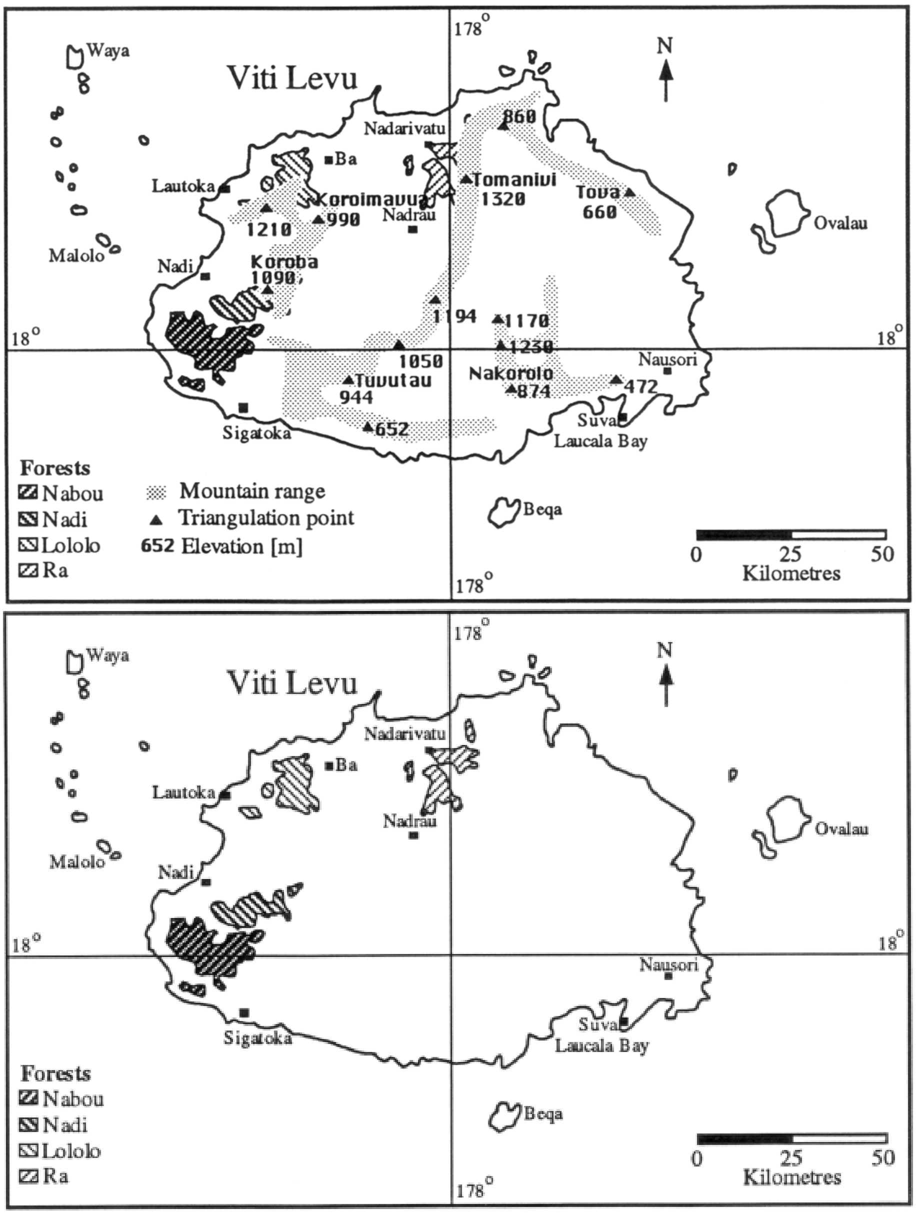


Figure 2.1: *Location of the major mountains and mountain ranges (top) and those of the various forest estates from the Fiji Pine Ltd. (bottom) in Viti Levu, Fiji.*

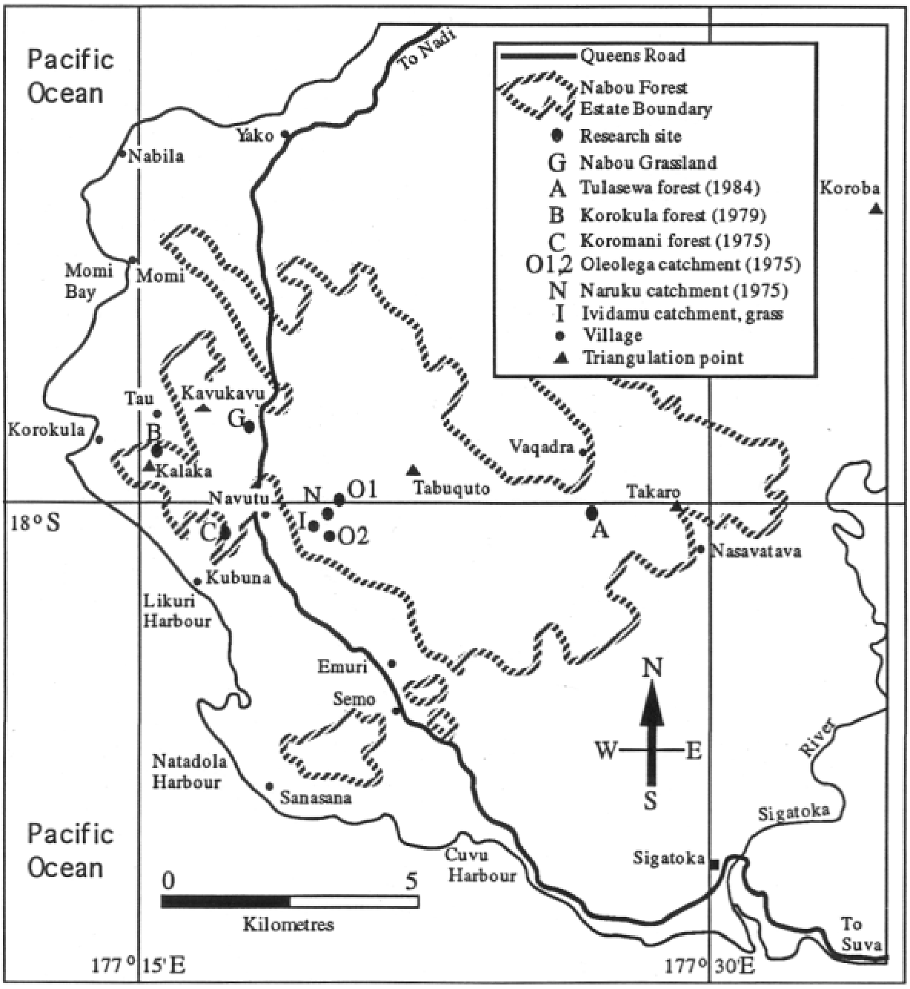


Figure 2.2: *Location of the Nabou grassland, the Tulasewa, Korokula, and Koromani forest plots, and the Oleolega, Naruku and Ividamu catchments within the Nabou Forest Estate boundary.*

the coast, to about 500 m a.s.l. in the Northeast. The area is mainly drained by one major river (Tuva river) and several smaller rivers and creeks (*e.g.* the Kubuna river, which drains the area surrounding the Oleolega catchment). The drainage pattern varies from dendritic to trellised, possibly reflecting the pattern of faulting within the various geological formations. Rivers and streams are generally deeply incised in V- or U-shaped river valleys, and only show a relatively broad valley bottom upon reaching the coastal lowlands.

2.2 Regional Geology

The following description of the geology has been taken largely from Hathway and Colley (1989), who gave a detailed description of the geology of SW Viti Levu, and to a lesser extent from Rodda (1989) who described that of the Fiji group as a whole.

From the Late Eocene to the Late Miocene the Fiji islands were part of a continuous Melanesian island arc, which included the New Hebrides island arc, the Fiji platform and the Lau-Tonga island arcs. The arc broke up late in the Miocene or very early in the Pliocene and the present tectonic situation is shown in Figure 2.3.

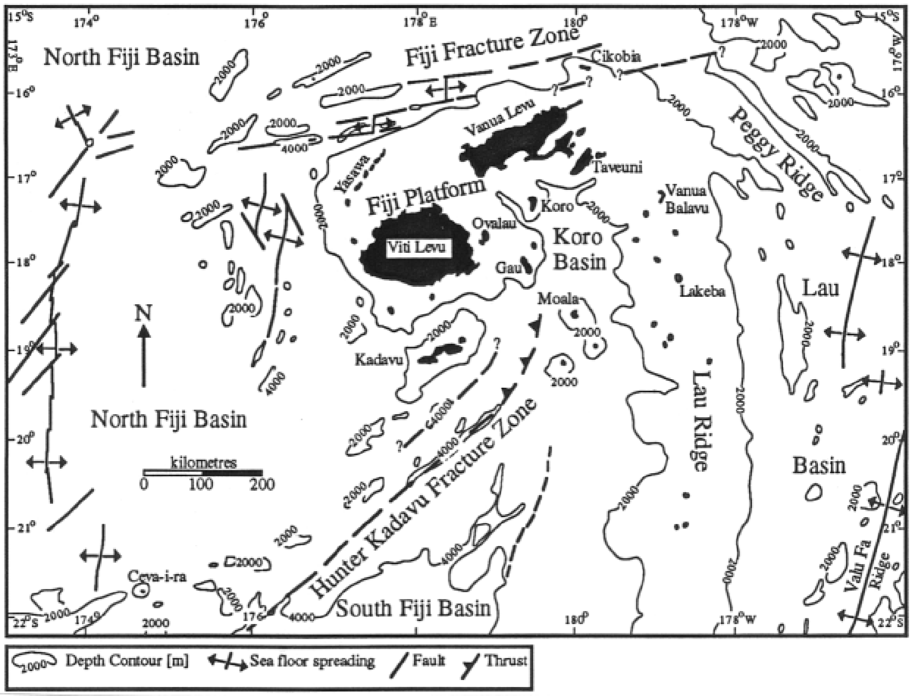


Figure 2.3: *Present regional tectonic setting of the Fiji archipelago (after Rodda, 1989).*

The Fiji group covers two major structural units, being the Fiji platform on which the main islands of Viti Levu and Vanua Levu are situated, and the Lau ridge which is separated from the Fiji platform in the East by the Bligh water basin with a depth of about 1000 m. Smaller units are the Kadavu group and various other islands and reefs in the Koro basin (Figure 2.3) which all rise from waters more than 2000 m deep (Rodda, 1989) . The Fiji platform is separated from the North Fiji basin (Pacific plate) by a passive margin in the West and by the Fiji Fracture zone in the North. In the South the platform is separated from the South Fiji basin by the Hunter Kadavu Fracture zone. The Lau ridge is separated from the Tonga ridge in the East by a passive margin in the Lau basin. The geology of the southern part of Viti Levu is dominated by intruded Oligocene and Miocene volcanic arcs, separated by a Miocene intra-arc basin in which sedimentation occurred. Rocks in the northern part of Viti Levu, on Vanua Levu and on the smaller islands in the Koro Sea and Lau ridge were deposited by Late Miocene to Late Pliocene volcanism and accompanied by a phase of erosion and sedimentation. Late Pliocene to Early Quaternary volcanism occurred on Vanua Levu, Taveuni and Kadavu only. Recent Quaternary deposits consist mainly of delta and mangrove deposits along the coasts of Viti Levu and Vanua Levu. A discussion of the stratigraphy of SW Viti Levu is given below, which is a modified version (Hathway and Colley, 1989) of that of Houtz (1959). A geological map of SW Viti Levu, based on the maps of Hathway and Colley (1989) and Rodda and Band (1966) is given in Figure 2.4.

The stratigraphy of SW Viti Levu can be divided roughly into seven groups, which have been dated on fossils found in the various formations. Some of the groups are laterally equivalent (*e.g.* the Navosa and Nadi groups), having been deposited in the same period but in different basins.

Yavuna Group: The oldest rocks in Fiji are exposed in SW Viti Levu and formed part of an active volcanic arc basement (Yavuna arc) at an early stage of evolution during the Upper Eocene to Lower Oligocene. The axis of the Yavuna arc stretches from NW to SE (Figure 2.4) as indicated by intrusions (tonalite stock and doleritic dikes). The Yavuna group consists mainly of massive and pillowed basalt lavas, basaltic andesite lavas, pillow breccias and some sediments (*e.g.* volcaniclastic rudites and shallow water limestones) and has undergone greenschist to lower amphibolite facies metamorphism.

Wainimala group: During the Upper Oligocene and the Middle Miocene a second volcanic arc (Wainimala arc) formed in the South with its axis nearly parallel (WNW–ESE) to that of the Yavuna arc (Figure 2.4). Both arcs were separated by a small fault-bounded sedimentary basin (Sigatoka Basin). The Wainimala group overlies the Yavuna group with angular unconformity at its southwestern margin (Hathway and Colley, 1989). The group consists of a volcanic arc assemblage (Tari formation) and a basinal assemblage (Nabu formation), for the most part separated by faults.

Rocks of the arc assemblage show phrenite – pumpellyite to greenschist metamorphism whereas those of the basinal assemblage generally show zeolite facies alteration. The Tari formation is considered to be the coarse dispersal apron of the Wainimala arc and consists of deposits of high density mass flows (volcaniclastic rudites), pillowed and massive basic to acid andesite lavas, dacite lavas and feldspar-porphyric dacites (Kalaka dacite). One substantial (Tau reef) and several smaller limestone bodies (*e.g.* Koromani reef) are part of the Tari formation and were deposited along the southern margin in the early Middle Miocene when the arc was uplifted and eroded during the Lower Miocene. Kalaka dacite appears as discrete lenses within the Tari formation and is massive with well-developed columnar jointing. It occurs at a high level in the Wainimala arc sequence and represents a more mature arc situation.

The basinal assemblage of the Wainimala group consists of the Dakadaka basalt

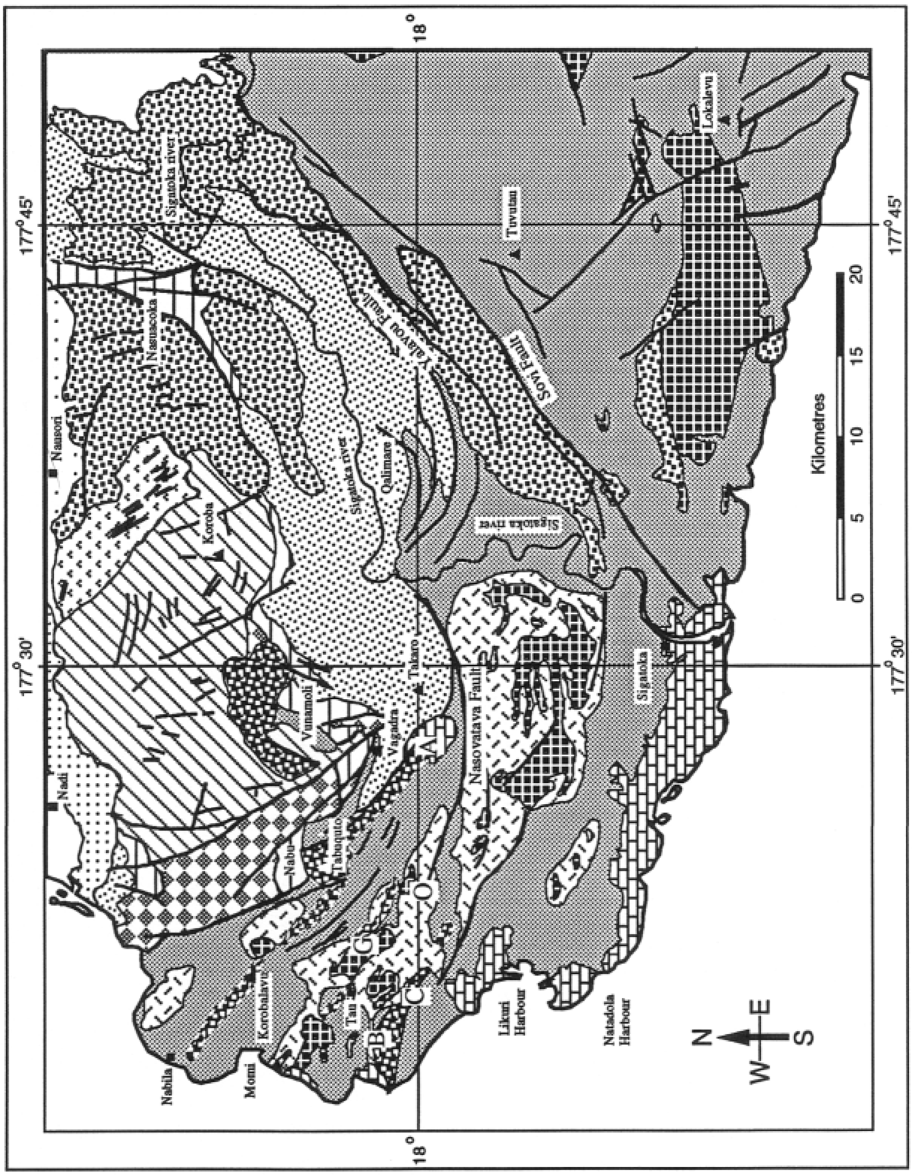
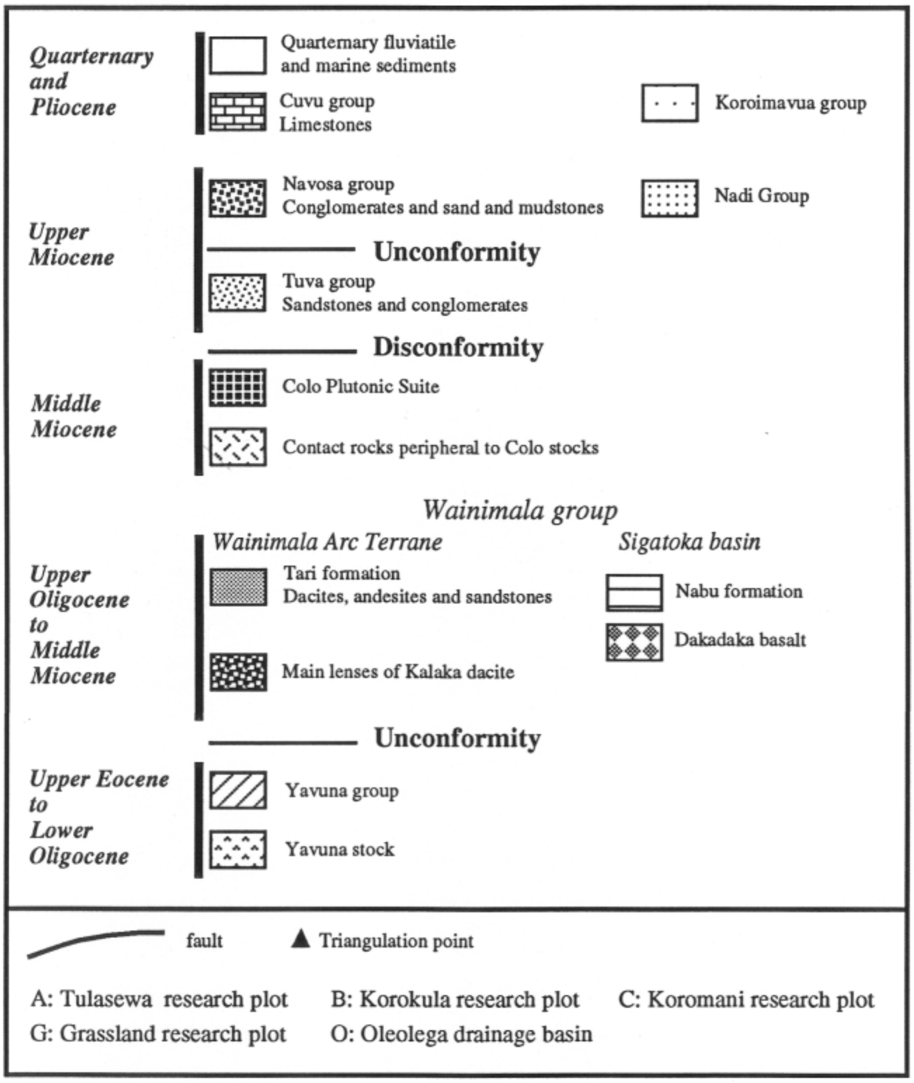


Figure 2.4: *Geological map of SW Viti Levu based on Hathway and Colley (1989) and Rodda and Band (1966).*


Quarternary and Pliocene
Quarternary fluviatile and marine sediments
Cuvu group Limestones
Koroimavua group
Upper Miocene
Navosa group Conglomerates and sand and mudstones
Nadi Group
Unconformity
Tuva group Sandstones and conglomerates
Disconformity
Middle Miocene
Colo Plutonic Suite
Contact rocks peripheral to Colo stocks
Wainimala group
Wainimala Arc Terrane
Sigatoka basin
Upper Oligocene to Middle Miocene
Tari formation Dacites, andesites and sandstones
Nabu formation
Dakadaka basalt
Main lenses of Kalaka dacite
Unconformity
Upper Eocene to Lower Oligocene
Yavuna group
Yavuna stock
fault
Triangulation point
A: Tulasewa research plot
B: Korokula research plot
C: Koromani research plot
G: Grassland research plot
O: Oleolega drainage basin

which is overlain by sediments of the Nabu formation. The Dakadaka basalt formed the exposed floor of the western part of the Sigatoka basin, and consists of pillow and massive lavas and pillow breccias. The basalts are often highly amygdaloidal and contain phenocrysts of plagioclase, clinopyroxene and pseudomorphic olivine. Amygdales are filled by calcite, analcime or fibrous zeolites. The Nabu formation has been divided into the Yako and Vagadra members. The Yako member overlies the Dakadaka basalt and consists of quartz poor, volcaniclastic turbiditic sandstone (tuffs) at the base, grading up to mudstone and hemipelagic carbonaceous mudstones and wackestones at the top of the member. The Vagadra member gradually overlies the Yako member and includes a greater proportion of turbiditic sandstones with somewhat increased feldspar contents and minor carbonaceous mudstones. The greater proportion of sandstones in the Vagadra member indicates an increase in terrigenous input into the Sigatoka basin. The uplift continued and a continuous horizon of limestones (Qalimere limestones) formed at the top of the Wainimala sequence. Remnants of this horizon are found along the southern margin of the Sigatoka basin.

Colo Plutonic Suite: Between Early Miocene and Late Miocene no record exists of major volcanism or sedimentation in SW Viti Levu. However, in the Late Middle Miocene and Early Late Miocene tonalite–gabbro intrusions occurred along the axis of the WNW-ESE faulted anticlinorium of the Wainimala arc, accompanied by emergence and probably folding and faulting. These plutonic intrusions have been classified as the Colo Plutonic Suite and are surrounded by areas of altered Wainimala wall rock. The small outcrops in SW Viti Levu are considered to be part of an continuous, incompletely unroofed pluton.

Tuva group: The deposition of sediments in the Sigatoka basin recommenced in the Late Miocene due to rapid erosion of the intruded Wainimala arc caused by major uplifting. The Tuva group consists of sandstones (Cici formation) and conglomerates (Takaro formation) with minor mudstones, which were deposited without apparent unconformity on Wainamala rock in a submarine environment (turbidites on a submarine fan).

Navosa group: A phase of folding and faulting occurred in the Late Miocene affecting both the Wainimala and Tuva groups. The faults (strike–slip system) and folds show an arcuate pattern around the Yavuna block, which may have acted as a resistant core around which the younger rocks were deformed. Conglomerates of the Navosa group were deposited with angular unconformity on the Yavuna, Wainimala and Tuva groups. Outcrops of this group are mainly found in the Sovi trough, which is folded into a syncline. The trough is bounded by the NE–SW striking Sovi fault in the SE and the northwestern margin is marked by an angular unconformity. The conglomerates consist of material derived from the Colo and Wainimala groups. To the north of the Sovi trough some andesite lavas intruded the Yavuna group and Navosa sediments there are dominated by basaltic and andesitic rudites.

Nadi group: Nadi sediments were deposited north of the Yavuna arc in the Nadi sedimentary basin in the Late Miocene. The deposits are the lateral equivalents of those of the Navosa group and possibly of the Tuva group as well. The sediments consist of debris of the Yavuna and Wainimala groups (breccias overlain by turbidite sand- and mudstones).

Table 2.1: *Averages, standard deviations and ranges of chemical and soil physical parameters of the topsoils (0–30 cm) and B/C-horizons (30–70 cm) of 22 pedons in the Nabou Forest Estate (after Leslie* et al.*, 1985).*

	pH	pH*	C %	N %	C/N	P ppm	P* %	Fe %	Al %	Exchangeable bases meq/100g soil **Ca**	**Mg**	**K**	**Na**	CEC	Theta pF=4.2 %
Topsoil (0-10/20 cm)															
Average	5.2	4.4	1.96	0.16	12.9	4.9	30	0.34	0.15	5.9	6.0	0.36	0.37	17.1	16.1
SD	0.5	0.4	0.72	0.05	3.2	2.1	15	0.31	0.07	2.9	4.6	0.28	0.12	5.9	6.6
Minimum	4.2	3.6	0.70	0.05	6.4	1.4	1	0.06	0.05	2.2	0.6	0.07	0.09	6.4	4.8
Maximum	6.3	5.1	3.95	0.26	17.4	10	52	1.52	0.34	13.2	17.7	1.19	0.55	26.9	30.3
Subsoil (30-70 cm)															
Average	5.7	4.3	0.17	0.04	4.7	2.3	32	0.21	0.12	3.6	8.2	0.10	0.43	17.9	18.2
SD	0.9	0.3	0.10	0.03	3.2	1.0	15	0.22	0.06	3.5	11.1	0.07	0.21	13.0	7.8
Minimum	4.1	3.5	0.02	0.01	1.0	0.3	0	0.01	0.03	0.2	0.8	0.01	0.03	5.5	2.8
Maximum	7.1	4.8	0.36	0.12	13.5	3.6	59	0.79	0.29	14.6	36.8	0.25	0.93	45.3	31.1

pH*: pH(KCl); P determined in 0.025M H_2SO_4 (Morrison and Dandy, 1979); P* is P retention
Exchangeable cations and CEC determined in NH_4Ac; Fe, Al determined in Tamm's extract
Theta: volumetric moisture content at wilting point (pF=4.2)

Cuvu group: Marine deposits (limestones and marls) of the Cuvu group were deposited in the Pliocene. Remnants of these deposits in SW Viti Levu are mainly found near the coast (Houtz, 1959).

2.3 Soils

There is a large variety of soil types in Fiji as a result of differences in topography, climate, substratum, erosion rates and vegetation cover (Twyford and Wright, 1965). Most soils are derived from *in situ* weathering of parent rock, which consists mainly of volcanic material or derived sediments.

Descriptions of 26 representative pedons in the Nabou Forest Estate were made by Leslie *et al.* (1985). Shallow (0.3–1.0 m), poorly developed soils are generally found on ridges and steep slopes, where erosion rates are relatively high and the availabilty of moisture frequently low, limiting the growth of vegetation. Somewhat deeper soils (0.8-1.5 m) are found in more gently sloping areas and in the valleys of rivers and creeks.

Soil colour generally varies from yellowish brown to reddish brown. The soils on ridges and slopes are well to moderately drained, although poorly drained dark soils occur locally in discharge zones and in small depressions. The infiltration capacity of undisturbed soil is usually high due to a well developed granular structure in the upper 20–30 cm of the soil and the erodibility is therefore considered low (Morrison and Clarke, 1990). Surface erosion seems the most common form of erosion, although landslides occur frequently during periods of torrential rainfall. Soil texture varies from fine sandy to clayey with most soils being classified as clay loam. Averages, standard deviations and ranges of chemical and soil physical features of the topsoils and the B/C-horizons for 22 pedons are presented in Table 2.1. The spatial variability of all soil parameters is very high as indicated by the large differences between minimum and maximum values. On the average pH_{H2O} increased slightly with depth whereas the pH_{KCl} remains constant and was typically about one unit lower. Carbon and nitrogen levels are highest in topsoil and decrease sharply with depth. The bulk of exchangeable bases in the soil consists of Ca and Mg, with low values for K and Na. Exchangeable K decreases sharply with depth in the profiles.

2.4 Climate

The climate of Fiji is maritime tropical. East to southeasterly low-level tradewinds blow throughout the year with slightly higher windspeeds during the cool, dry season (May–October) than during the warm, wet season (November–April). Northeasterly winds (anti-trades) blow at a higher level in the atmosphere (troposphere) and large-scale weather systems usually move with these upper winds. The group is affected by tropical cyclones almost every year with two to three severe cyclones with hurricane force winds passing every decade. Cyclones are often accompanied by torrential rains and their occurrence is restricted to the wet season when ocean surface temperatures are high enough to provide the energy for the initiation and maintenance of these systems (Gray, 1968, 1988). The average sea surface temperature ranges from 25°C in August to 28°C in March (Basher, 1986b). The air temperature and relative humidity vary little between seasons. Rainfall is seasonal and shows a high spatial as well as temporal variability. Annual rainfall totals range from 1800 to 5000 mm yr^{-1}.

The climate of the smaller islands is fairly uniform as air temperature and humidity fluctuations are attenuated by the presence of the ocean. As these islands are low, orographic effects are minor and annual rainfall amounts range between 2000 and 3000 mm $year^{-1}$.

On the larger mountainous islands (*e.g.* Viti Levu, Vanua Levu and to a lesser extent Taveuni and Kadavu) orographic effects are important. The climate of Viti Levu is influenced by NNE–SSW stretching mountain ranges with elevations ranging from 930 m in the South to 1320 m in the North (Figure 2.1), resulting in different climates on the windward (humid) and leeward (dry) sides. The climate of Viti Levu will be discussed in detail below, using data from contrasting climate stations operated by the Fiji Meteorological Service in these areas.

The data from the coastal Laucala Bay station (18°09'S, 178°27'E, 6 m a.s.l.) and the more inland Nausori Airport station (18°03'S, 178°34'E, 3 m a.s.l.) are representative for the climate at the humid windward side of Viti Levu. Both stations are located in the SE near Suva. The data from Nadarivatu (17°34'S, 177°57'E, 835 m a.s.l.) and Nadrau (17°43'S, 177°57'E, 777 m a.s.l.) in the North are representative for the climate in the highlands, whereas the data from Nadi Airport (17°45'S, 177°27'E, 16 m a.s.l.), a coastal station in western Viti Levu, is representative for the climate at the dry leeward side (Figure 2.1). As the present study was conducted on the leeward side of Viti Levu the climate at Nadi Airport will be described in more detail than those of the windward and highland sites.

2.4.1 Rainfall

The annual rainfall distribution over Viti Levu is shown in Figure 2.5. At the windward side (SE Viti Levu) forced lifting of air against the mountain slopes and subsequent condensation causes frequent rainfall which results in a persistently humid climate

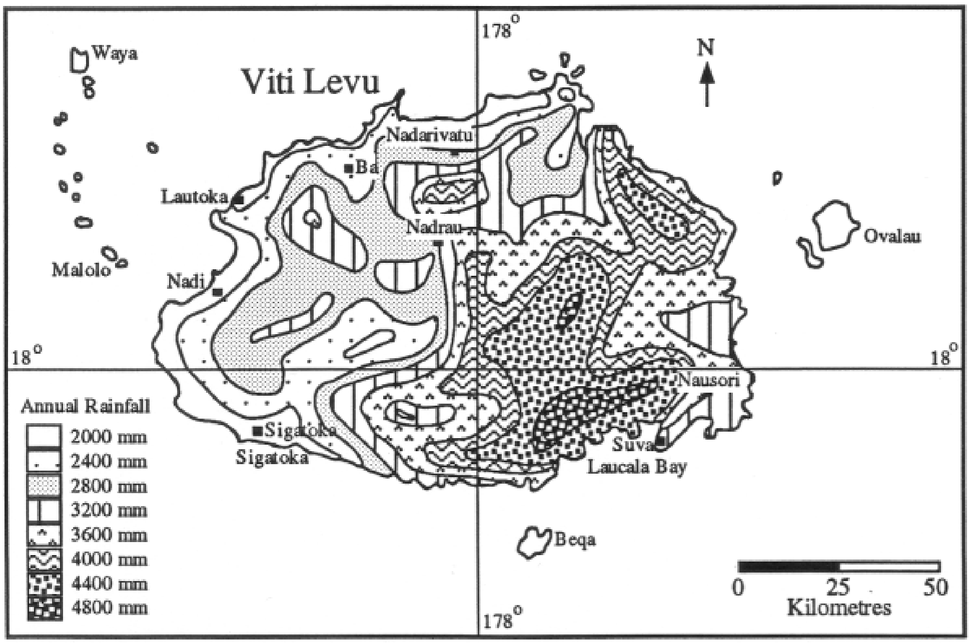


Figure 2.5: *Distribution of annual rainfall totals over Viti Levu.*

with an annual rainfall total of 3019 mm (1942–1973) at Laucala Bay. Annual rainfall totals are highest on the windward slopes of the mountains where rainfall can exceed 5000 mm yr^{-1} (*e.g.* Mt. Nakorolo). Nadarivatu, in the northern highlands, receives 3612 mm of rain annually (1910–1980). The relatively dry leeward side has an average annual rainfall total of 1872 mm (1942–1979) at Nadi Airport. Table 2.2 shows monthly rainfall totals and the number of rain days (rainfall exceeding 0.1 mm) for three contrasting stations. The climate on the windward side experiences monthly rainfall of well above 100 mm and a minimum of 16 rain days in August. In contrast, the leeward side experiences a distinct dry season from May until October with monthly rainfall totals well below 100 mm and a monthly average of 6 rain days during the dry season. Rainfall amounts for the lowland stations are similar from January to March. The rainfall regime at Nadarivatu (835 m a.s.l.) is more extreme. During the dry season rainfall totals are in between those of the windward and leeward sides. However, during the wet season rainfall amounts increase sharply to up to two times those recorded in the lowlands. As the number of rain days at Nadarivatu is similar to those at the lowland stations, rainfall intensity and duration should increase with elevation.

Rainfall is very variable in time as shown by the large standard deviations of monthly rainfall at Nadi Airport (Figure 2.6), where annual totals ranged from 998 mm (1987) to 2984 mm (1974) between 1973 and 1989. A frequency distribution of daily rainfall totals at Nadi Airport is shown in Figure 2.7. Daily totals were usually (62%) below 10 mm and exceeded 150 mm on five days (2.1%) in 17 years with a maximum of 301 mm on March 1, 1983, during the passage of cyclone Oscar. Data on the diurnal rainfall distribution was not available for any of the climate

Table 2.2: *Monthly rainfall (mm) and number of rain days at Laucala Bay (1942–1973), Nadarivatu (1910–1980) and Nadi Airport (1942–1979; After Coulter, 1981b,c).*

	Laucala Bay		**Nadarivatu**		**Nadi Airport**	
	Rainfall	Raindays	Rainfall	Raindays	Rainfall	Raindays
January	308	23	565	20	299	18
February	327	21	667	21	286	18
March	377	23	708	23	353	19
April	373	22	336	16	180	13
May	233	20	164	12	84	8
June	173	17	98	9	71	5
July	153	17	81	7	48	4
Augustus	132	16	118	8	58	5
September	201	17	134	9	90	7
October	209	18	139	10	96	9
November	258	18	236	13	139	11
December	275	20	366	18	168	14
Total	**3019**	**232**	**3612**	**167**	**1872**	**131**

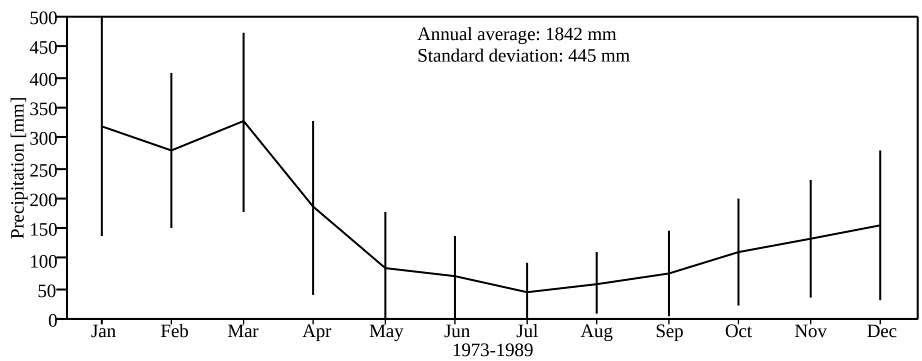


Figure 2.6: *Average monthly rainfall and standard deviations (mm) for Nadi Airport (1973–1989; source: Fiji Meteorological Service, Nadi).*

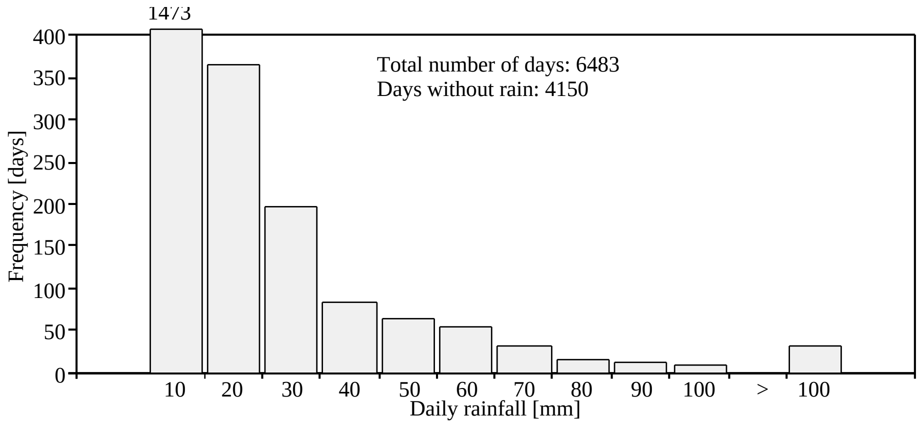


Figure 2.7: *Frequency distribution (days) of daily rainfall totals at Nadi Airport (1973–1989; source: Fiji Meteorological Service, Nadi).*

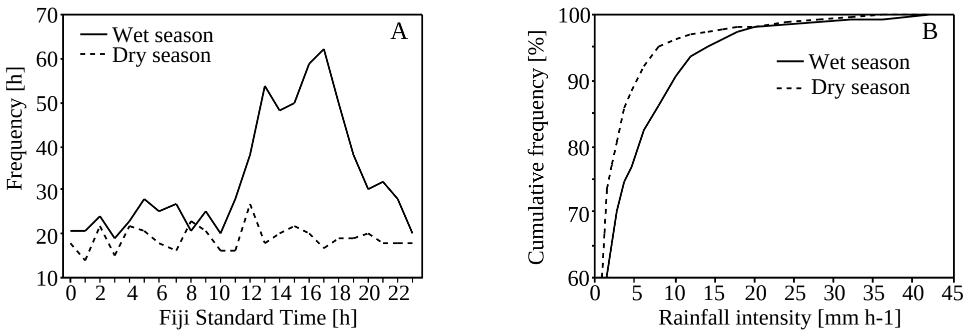


Figure 2.8: *Diurnal rainfall distribution (A) and cumulative frequency of rainfall intensity (B) at Oleolega drainage basin (January 1990 – March 1992).*

stations. However, throughout the present study (27 months) hourly rainfall amounts were recorded at the Oleolega drainage basin (Figure 2.2) by a tipping bucket rainfall recorder. The diurnal rainfall distribution and the cumulative frequency distribution of rainfall intensities at this site are shown in Figures 2.8A and 2.8B, respectively. During the dry season rainfall occurrence is distributed equally during the day and intensities are low as rainfall is mainly caused by slow moving large scale weather systems. During the wet season short duration, high intensity convective rain showers frequently occur in the afternoon which results in a peak in the rainfall distribution around 17:00 h.

2.4.2 Temperature and Humidity

The annual average temperature at the windward side is 24.5(±1.3) °C (Nausori Airport near Suva 1973–1979; Coulter, 1981a), whereas that at the leeward side is slightly

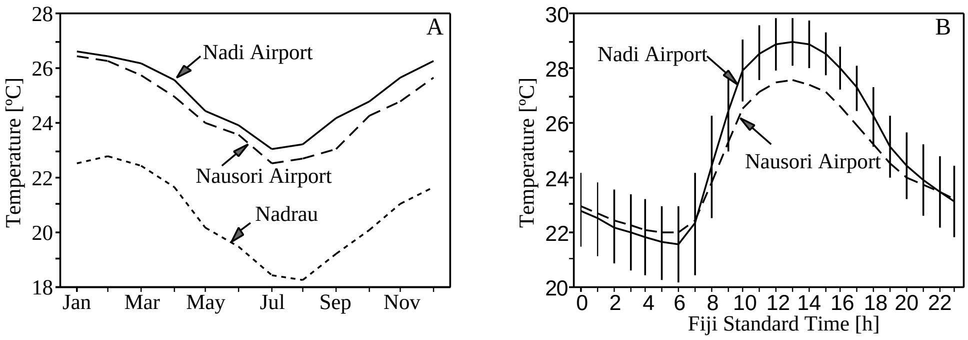


Figure 2.9: *(A) Monthly averages of temperature (° C) at Nadi Airport (16 m), Nausori Airport (6 m) and Nadrau (777 m) and (B) diurnal courses of temperature at Nadi Airport (with standard deviations) and Nausori Airport.*

higher at 25.0(±1.2) °C (Nadi Airport 1960–1979; Coulter, 1981a). Temperatures in the highlands are lower with an annual average of about 20.7(±1.5) °C at Nadrau (elevation 777 m, 1977–1983; Coulter, 1984; see Figure 2.1 for locations), implying an annual average temperature lapse rate of 5.5 °C km^{-1}. Monthly averages for Nausori Airport, Nadi Airport and Nadrau are shown in Figure 2.9A. There is a distinct seasonal pattern with a temperature range of some 4 °C as monthly averages of temperature in the lowlands range from 22.8 °C in July to 26.5 °C in January.

The diurnal courses of temperature at the lowland stations are shown in Figure 2.9B. A rapid increase in temperature from an early morning minimum of 22 °C to a maximum at noon of 27–29 °C can be observed, followed by a much slower return to the early morning minimum during the afternoon and night. Hourly values were not available for any of the highland stations but a similar diurnal pattern, although at lower temperatures, can be expected. The diurnal range is larger in the dry zone, with a range of 7.5 °C at Nadi Airport, than in the wet zone, with a range of 5.6 °C at Nausori Airport. The average daily minimum temperatures for the coldest month (July) are 20.4 °C at Laucala Bay, 18.3 °C at Nadi Airport and 14.6 °C Nadrau. The highest mean daily maximum temperatures occur in January and are 30.5 °C, 31.5 °C and 26.6 °C at Laucala Bay, Nadi Airport and Nadrau respectively (Reddy, 1989d). Standard deviations of the average daily temperature, obtained from hourly values, range from 1.0 °C to 2.4 °C (Krishna, 1981) at Nadi Airport.

The annual average relative humidity, obtained from monthly averages of hourly readings, was 79(±3)% at Nadi Airport (Gabites, 1977) and 84(±2)% at Laucala Bay (Basher, 1986a). Monthly averages of hourly readings were not available for Nadarivatu or Nadrau. However, an estimate was obtained by multiplying the monthly average of the relative humidity, as measured at 9:00 h at Nadarivatu (Figure 2.10), times the ratio of monthly average relative humidity (hourly readings), to the 9:00 h monthly average relative humidity at Laucala Bay. This ratio shows a seasonal variation ranging from 1.02 in June to 1.07 in December and application of these figures resulted in an annual average relative humidity of 89(±2)% at Nadarivatu.

Monthly averages of the 9:00 h relative humidity at Nadi Airport, Laucala Bay and Nadarivatu are shown in Figure 2.10A. The variation between months is low at the windward side and in the highlands with a 5–7% difference between the dry

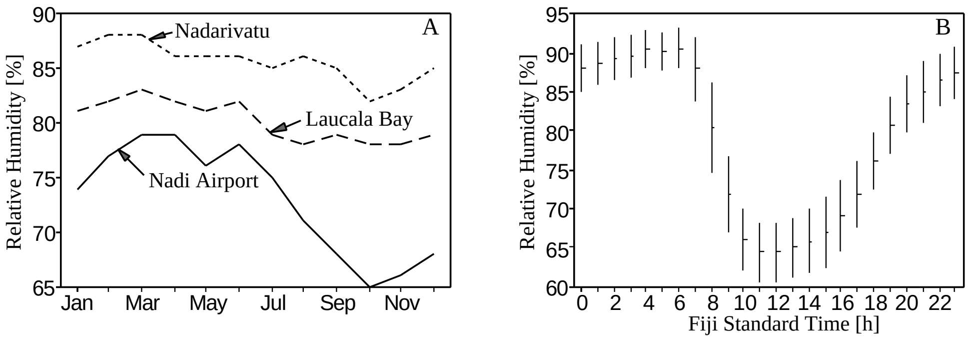


Figure 2.10: *(A) Monthly averages of relative humidity (%), measured at 9:00 h at Laucala Bay, Nadi Airport and Nadarivatu and (B) the mean diurnal course and standard deviations of relative humidity (%) at Nadi Airport (1960–1979).*

season minimum and the wet season maximum. The monthly averages at the leeward side show a distinct seasonal pattern with an 18% difference between the dry season minimum and the wet season maximum.

Hourly averages and standard deviations of relative humidity at Nadi Airport (1960–1969) are shown in Figure 2.10B. The relative humidity is highest just before sun rise (90% at 6:00 h) and shows a rapid decrease in the morning, corresponding with a rapid increase in the temperature, to a minimum of 65% around noon, after which a gradual return to the early morning maximum occurs. The high early morning humidity frequently causes condensation of moisture (dew) on the grassland vegetation in the dry zone of Viti Levu.

2.4.3 Sunshine Duration and Short-wave Radiation

The annual average daily sunshine duration (n), as measured with Campbell-Stokes sunshine recorders, ranges from 5.2 h day^{-1} on the windward side (Laucala Bay, 1943–1988) to 6.9 h day^{-1} on the leeward side (Nadi Airport, 1947–1988) with intermediate values in the highlands (5.4 h day^{-1} at Nadrau (1977–1988); Reddy, 1989e). The maximum possible sunshine duration (N) ranges from 11.1 h day^{-1} in June to 13.1 h day^{-1} in December (Smithsonian Meteorological Tables, Table 171; Kijne, 1974).

Monthly percentages of relative sunshine duration (n/N) for the three contrasting stations are given in Figure 2.11. The percentages are low on the windward side due to the frequent presence of clouds and vary little between months, whereas those on the leeward side are much higher and show a distinct seasonal pattern. The variation of n/N at Nadrau reflects the extreme rainfall regime with very low values during the wet season and intermediate values during the dry season.

The diurnal sunshine patterns for the lowland stations are shown in Figure 2.12A (wet season) and 2.12B (dry season). The development of clouds in the afternoon during both seasons is clearly illustrated by the sudden decrease in the average fractions of hourly sunshine after 13:00 h. This effect is strongest on the leeward side during the wet season (Figure 2.12A), where morning skies are usually clear and clouds do not build up until after 13:00 h. During the wet season the average hourly fractions of sunshine on the windward and leeward sides are similar after 14:00 h, suggesting that

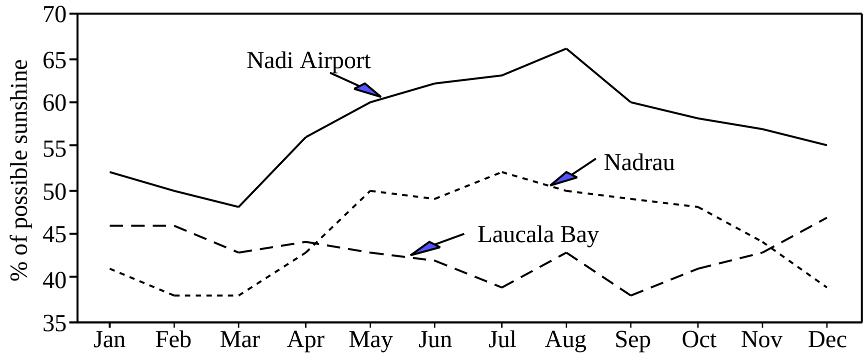


Figure 2.11: *Monthly percentages of relative sunshine duration (n/N) for Laucala Bay, Nadi Airport and Nadrau (Reddy, 1989e).*

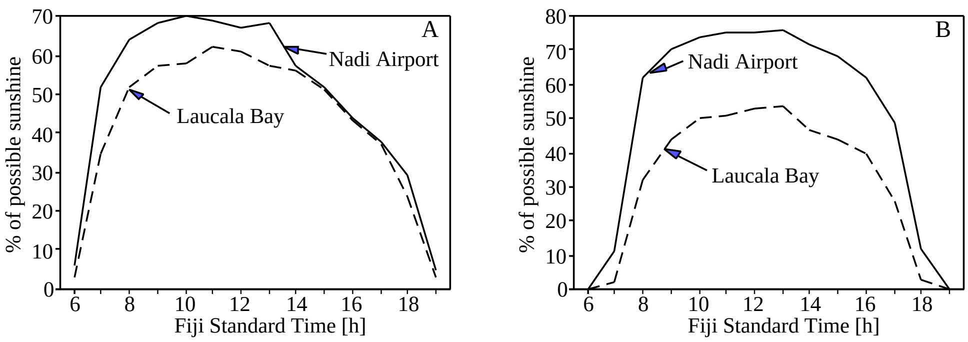


Figure 2.12: *Diurnal variation of wet season (A) and dry season (B) average hourly fractions of sunshine (%) for Nadi Airport and Laucala Bay (Singh, 1983).*

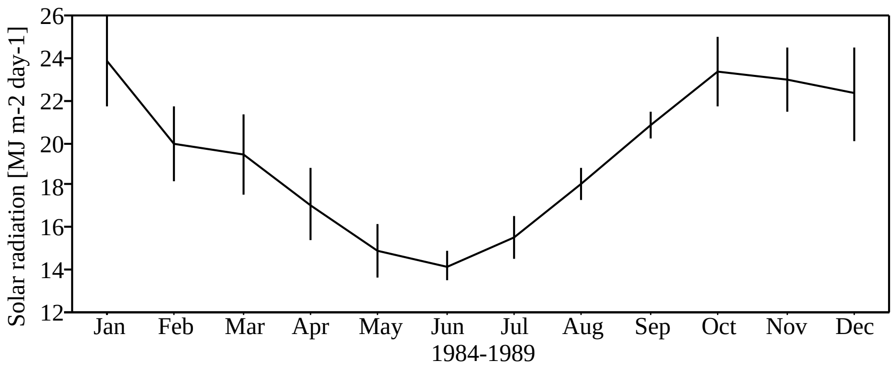


Figure 2.13: *Monthly averages and standard deviations of solar radiation ($R_s \downarrow$, in MJ m^{-2} day^{-1}) as measured at Nadi Airport (1984–1989; source: Fiji Meteorological Service, Nadi).*

the cloud cover usually extends over the whole island by that time. This phenomenon is not observed during the dry season when clouds develop mainly on the windward side of the island and the average hourly fractions of sunshine at Nadi Airport are therefore higher than those at Laucala Bay throughout the day (Figure 2.12B).

Daily short-wave radiation totals have been measured at Nadi Airport since 1983 with a Kipp & Zonen CM11 pyranometer and monthly averages and standard deviations (MJ m^{-2} day^{-1}) over the period 1983–1989 are shown in Figure 2.13. Solar radiation is highly seasonal with a maximum monthly mean of 23.9 MJ m^{-2} day^{-1} in the wet season and a minimum of 14.1 MJ m^{-2} day^{-1} in the dry season (Table 2.3). If direct measurements of solar radiation are not available, estimates can be obtained from measured sunshine durations using linear regression equations (Equation 2.1; Rietveld, 1978)

$$R_s \downarrow = (a + b \cdot n/N) \cdot R_{ET} \tag{2.1}$$

where $R_s \downarrow$ is the daily total of short-wave radiation (MJ m^{-2}), n is the actual sunshine duration (h), N is the daylength (h), R_{ET} is the incoming short-wave radiation at the top of the atmosphere (MJ m^{-2} day^{-1}, obtainable from tables, *e.g.* Smithsonian Meteorological Tables, Table 132; Kijne, 1974) and a and b are regression constants. The day length in Fiji ranges from 11.1 to 13.1 h day^{-1} in June and December, respectively, with corresponding R_{ET} values of 24.1 and 41.7 MJ m^{-2} day^{-1}. However, the month with the highest $R_s \downarrow$ is January due to lower sunshine durations in December as compared to those in January (Figure 2.13). Regression constants for two consecutive months in both the wet and the dry season were calculated from daily radiation totals and corresponding sunshine durations measured at Nadi Airport. Additional regression constants were determined for the calculation of the monthly average of daily solar radiation from the monthly average sunshine duration. The results are shown in Table 2.3. The constants a and b, the sum of which is a measure of the transmissive characteristics of the overlying air column, are similar to those found for other locations in the humid tropics (De Jong, 1973; Chia, 1974; Waterloo, 1989). Maps of the wet and dry season distributions of radiation totals over Viti Levu as calculated from sunshine durations (Gabites, 1978) are shown in Figure 2.14. The average daily incoming solar radiation in December is 21–23 MJ m^{-2} on the leeward side as opposed

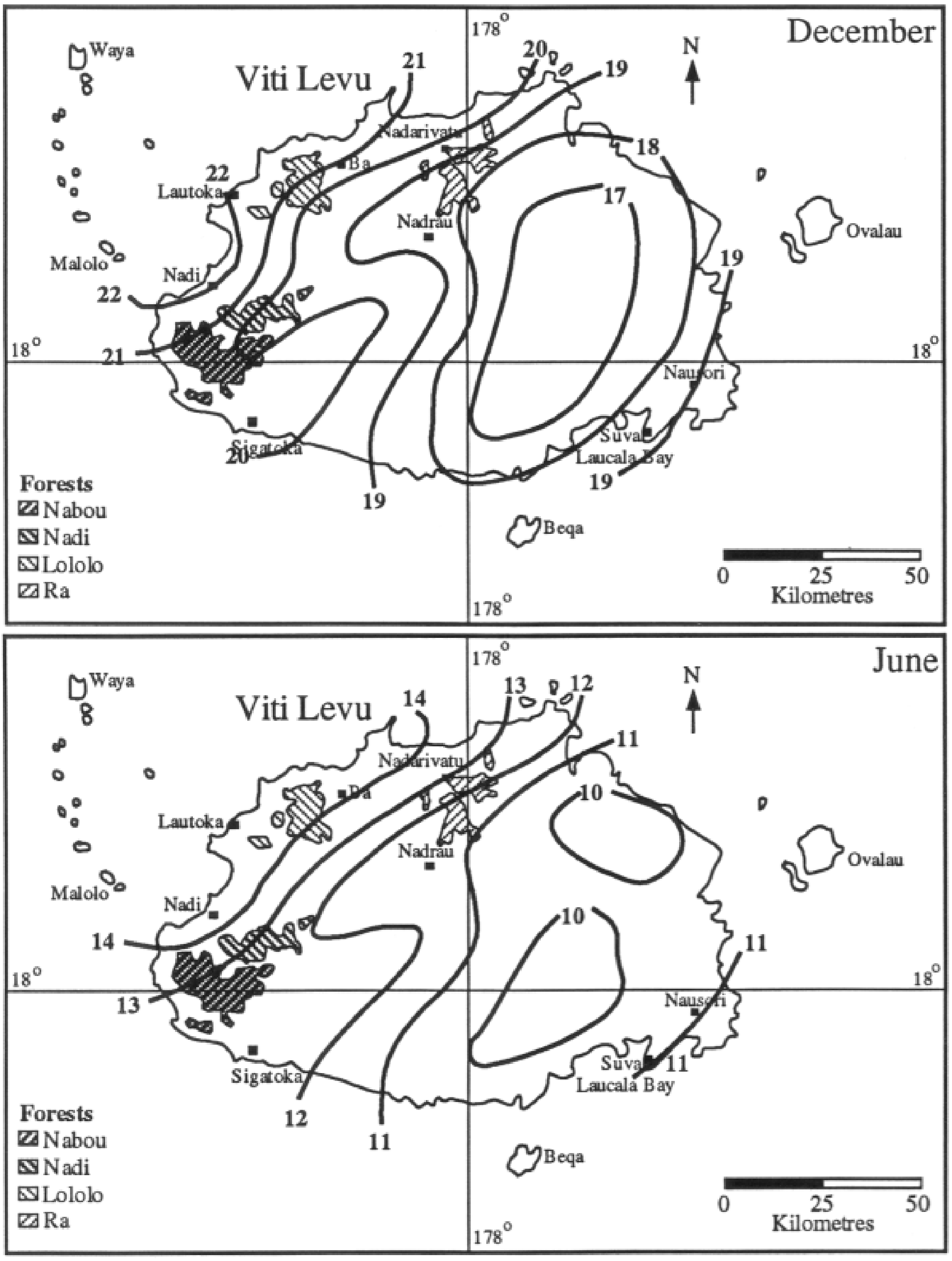


Figure 2.14: *Wet season (December) and dry season (June) distributions of short-wave radiation (MJ m^{-2} day^{-1}) over Viti Levu (after Gabites, 1978).*

Table 2.3: *Averages and standard deviations (SD) of the sunshine duration (n) and $R_s \downarrow$ (MJ m^{-2} day^{-1}) for two consecutive months in the wet and dry season as well as for the whole year, and regression constants (a and b) and standard errors of estimate (SE) for the calculation of daily and monthly $R_s \downarrow$ values (MJ m^{-2}) from measured n/N ratios.*

	a	SE	b	SE	r2	n	SD	Rg	SD
December	0.30	0.06	0.46	0.01	0.87	6.5	4.2	22.1	6.6
January	0.29	0.05	0.48	0.01	0.85	7.8	3.4	23.9	5.7
June	0.32	0.06	0.47	0.01	0.86	6.4	3.5	14.1	3.8
July	0.34	0.06	0.44	0.01	0.83	7.3	3.1	15.5	3.4
Monthly average	0.28	0.02	0.52	0.02	0.89	6.9	0.3	19.3	0.6

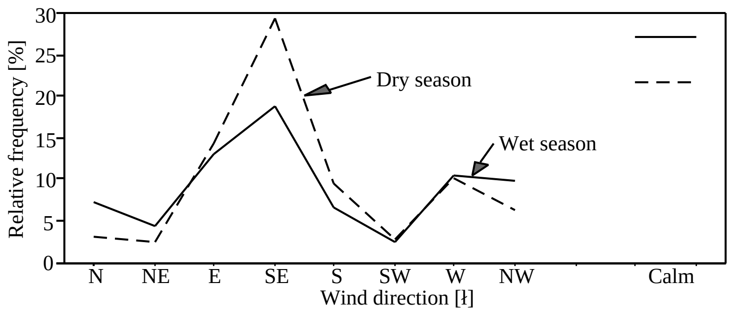


Figure 2.15: *Relative frequency of wind directions (%) for the dry season and wet season at Nadi Airport (1960–1984; Reddy, 1989b).*

to 16–19 MJ m^{-2} on the windward side and highlands. The corresponding totals for June are 14 MJ m^{-2} and 10–12 MJ m^{-2} respectively (Gabites, 1978).

2.4.4 Wind Direction and Speed.

The predominant winds over the Fiji group are east to southeasterly trade winds which blow throughout the year but are most pronounced during the dry season. Local daytime sea breezes with a west to northwesterly direction occur regularly near the coast on the leeward sides of Viti Levu and Vanua Levu. However, winds resulting from the land – sea interaction do not extend inland very far. The relative frequency (%) of wind direction, as measured at Nadi Airport from 1960 until 1984 (Reddy, 1989b), is shown in Figure 2.15. During the dry season both strong (daytime) and light winds (nighttime) have an east to southeasterly direction. During the wet season, however, the stronger winds (daytime) are usually from the west to northwest, which might be attributed to land – sea interaction. Half-hourly wind direction data collected by the present project above Tulasewa and Koromani forests in Nabou (Figure 2.2) showed a predominantly SE wind direction throughout the year (Section 7.3.2).

Wind speeds are generally low with an annual average (based on monthly averages) of 2.6(±0.3) m s^{-1} in Nadrau (Coulter, 1984) and 2.8(±0.4) m s^{-1} at Nadi Airport (Reddy, 1989a). Wind speeds are slightly higher during the dry season, with a maximum monthly average of 3.4(±1.4) m s^{-1} in October, than during the wet season, with a minimum monthly average of 2.4(±1.0) m s^{-1} in April. This is clearly illustrated in Figure 2.16A. The wind speed at Nadi Airport shows a distinct diurnal trend (Figure 2.16B) with a minimum of 1.7(±0.2) m s^{-1} in the early morning (4:00 h) and a maximum of 5.2(±0.5) m s^{-1} in the afternoon (14:00 h).

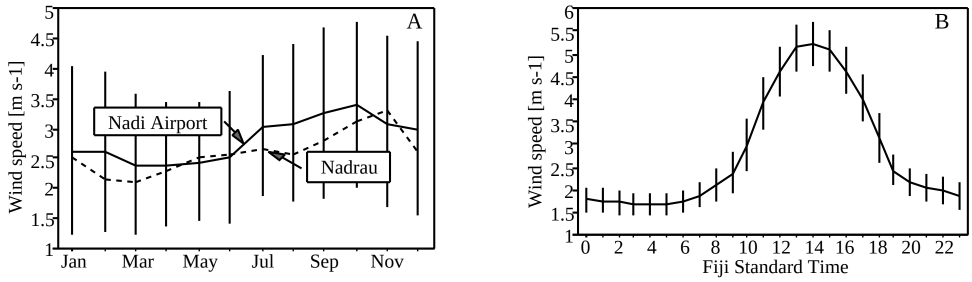


Figure 2.16: *(A) Monthly average wind speeds at Nadi Airport and Nadrau, and (B) the diurnal course of windspeed at Nadi Airport (standard deviations represented by vertical bars).*

Tropical cyclones usually develop in the Pacific Ocean to the W to NW of Fiji and move southeastwards to the Fiji group with the upper tropospheric winds. This is clearly shown in Figure 2.17 where the tracks of cyclones affecting the Fiji Islands during the last decade are shown. Extreme wind speeds occur during the passage of cyclones, with maximum 2–3 second gusts of up to 57 and 47 m s^{-1} at Nadi Airport (cyclone Arthur, 1981) and Laucala Bay (cyclone Eric, 1985) respectively (Basher, 1986c). Wind speeds usually diminish above land because of decreased evaporation, increased surface friction and changes in ground level air temperature (Anthes, 1982). When large differences in surface conditions exist, such as when part of a cyclone intersects mountainous terrain, assymetric radial pressure gradients develop and the cyclone may move away from the mountainous areas (Scatena and Larsen, 1991). Therefore cyclone intensities may be lower in the interior of the larger mountainous islands (Viti Levu and Vanua Levu) than in the coastal areas.

Between 1975 and 1989 five major cyclones have caused substantial damage to the forests in SW Viti Levu. Two cyclones passed through the Fiji group in 1990, one of which caused major damage. Tropical cyclone Rae formed about 400 km southwest of Fiji on March 18, 1990 and reached its peak intensity on March 23, when it was located 225 km south of Kadavu (Figure 2.17). As such the cyclone posed no direct threat to any inhabited island of Fiji, but the group experienced strong winds with a maximum hourly average of 16 m s^{-1} and maximum gusts of 25 m s^{-1} (Prasad, 1990). The magnitude of the maximum wind gusts indicated that the force of cyclone Rae was very common, with a return period of 2 years (Basher, 1985). The passage of the cyclone was preceded by torrential rains from March 20–23. In Nabou forest a total of 249 mm of rainfall was recorded over 4 days with maximum 5-minute, 30-minute and hourly rainfall intensities of 57.9, 40.6 and 27.9 mm h^{-1} at the Tulasewa forest plot (Figure 2.2), respectively. The highest rainfall was recorded in the interior of Viti Levu and amounted to 443 mm at Monasavu (Prasad, 1990).

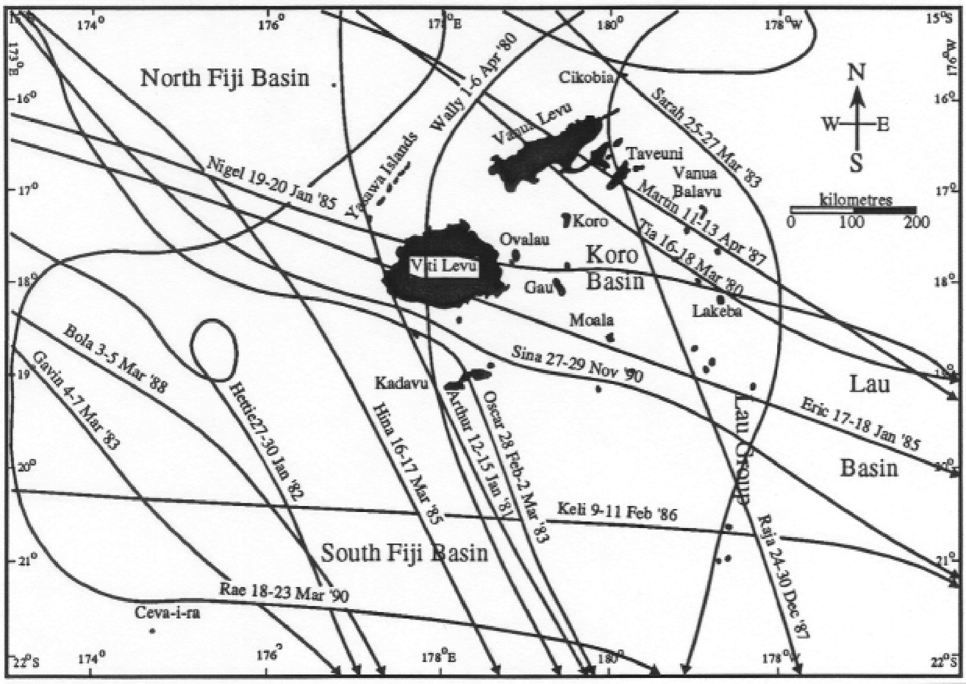


Figure 2.17: *Paths of tropical cyclones that have affected the Fiji group over the period Jan 1980 – December 1991 (Source: Fiji Meteorological Service).*

Tropical cyclone Sina formed some 1000 km southwest of Viti Levu on November 25, 1990 and passed along the western and southeastern parts of the Fiji Islands in the night of November 27–28 with a speed of 17 km h^{-1}. High wind speeds occurred during the passage of the cyclone with a maximum hourly average of 38 m s^{-1} measured in the early morning of November 28 (4:00 h) on a hill top near Koromani forest in SW Viti Levu (present study). The maximum mean wind speed sustained over a period of 10 minutes amounted to 66 m s^{-1}. Storm force winds were observed in Suva between 8:00 and 10:00 h with a maximum hourly average of 31 m s^{-1}. The wind direction was NE in the period preceding the passage of the cyclone and changed to NW in a 3-hour period during the passage of the cyclone at Koromani forest. The maximum gust was estimated at 84 m s^{-1} using an empirical factor of 1.4 (Basher, 1986c) resulting in a return period of 10 years for cyclone Sina (Basher, 1985). Most rainfall occurred in the 48 hours preceding the passage of the cyclone, whereas little rainfall was recorded during the actual passage. Total rainfall amounted to 136 mm with maximum 5-minute, 30-minute and hourly rainfall intensities 50.4, 44.2, and 22.0 mm h^{-1} at the Tulasewa forest plot, respectively.

2.4.5 Evaporation

The Penman formula (Penman, 1956; Appendix 22.2) allows the calculation of the open water evaporation (E_0) from daily or monthly averages of temperature, humidity, wind speed and global radiation. At Nadi Airport, where radiation inputs are high and the daytime relative humidity low, average E_0 amounts to an annual total of 1992 mm, which is slightly higher than the annual rainfall total of 1872 mm (Table 2.2). On the windward side (Laucala Bay, Nausori Airport) E_0 amounts to 1742 mm as a result of lower solar radiation inputs and higher relative humidity. The decrease in temperature with elevation further reduces E_0 to 1505 mm $year^{-1}$ in the highlands (Nadarivatu, Nadrau). Monthly E_0 values for the various stations are shown in Figure 2.18. E_0 reaches a minimum in June (2.8–3.8 mm day^{-1}) and is highest in December (5.0–6.9 mm day^{-1}), *i.e.* during the southern summer.

Monthly rainfall amounts (Table 2.2) are similar to or higher than the monthly open water evaporation totals (Figure 2.18) on the windward side and in the highlands. As such it is unlikely that the vegetation will experience severe water stress for long periods of time and the actual evapotranspiration will therefore be in the same order of of magnitude as E_0. At the leeward side monthly rainfall totals are much lower than E_0 during the dry season (May–October) and depletion of soil moisture in the course of the dry season may result in much lower actual evapotranspiration rates than those calculated with the Penman formula (*cf.* Part II).

2.5 Vegetation and land use

In the early 19^{th} century most Fijian villages were located along the coasts and it was only after the arrival of the Europeans that the Fijians moved to hillier areas more inland, where the original vegetation (some form of evergreen broadleaf forest; Twyford and Wright, 1965) was replaced by the present savannah and grassland vegetation as a result of slash and burn agriculture and cattle grazing. Remnants of forest can be found on some hillslopes but mostly along perennial streams in the dry zone. As fires occurred once every few years a fairly stable, fire resistant climax vegetation has developed, consisting mainly of grasses and ferns (Drysdale and Rawaqa, 1987). The

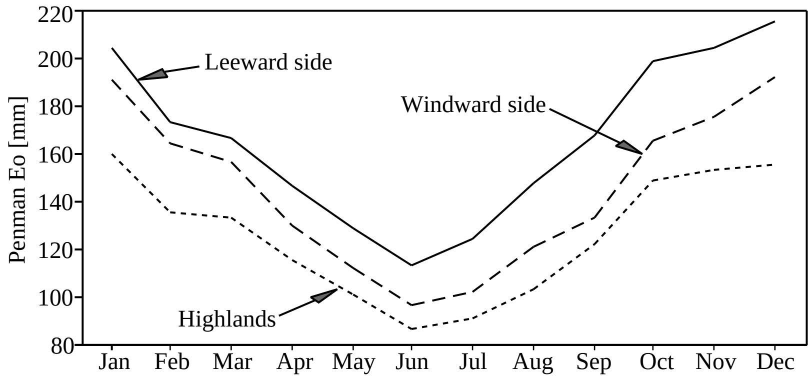


Figure 2.18: *Monthly averages of Penman open water evaporation on the windward side (Laucala Bay), the highlands (Nadrau) and the leeward side (Nadi Airport) of Viti Levu (based on data provided by the Fiji Meteorological Service in Nadi as shown in previous diagrams).*

repeated destruction of the vegetation by fires also caused degradation of the soils on hillslopes and ridges by accelarated erosion. These severely eroded, shallow soils of poor structure and fertility are locally called *talasiga* soils.

Flat to undulating terrain in the dry zone of Viti Levu is presently almost exclusively used for the cultivation of sugar cane. Near villages and on the banks of rivers and streams a variety of root crops (*e.g.* cassava, yams, taro), vegetables (*e.g.* cabbage, tomatoes) and fruits (*e.g.* mango, banana, pineapple) are cultivated in small plots, mostly for domestic use. Larger scale agriculture is limited to the broad valleys and flood plains of the larger rivers (*e.g.* Sigatoka and Nadi rivers). Since the 1950s *Pinus caribaea* plantation forests have been established on the more steeply sloping grassland areas in the dry zones of Viti Levu and Vanua Levu, which were not suitable for the cultivation of sugar cane. At present the total area under plantation on Viti Levu is 23,230 ha (Yabaki, 1991).

The grassland vegetation is often dense. The dominant species is mission grass (*Pennisetum polystachyon*) which was introduced by missionaries and soldiers. Mission grass can reach heights of up to 2 m at the end of the growing season and is often associated with bracken fern (*Dicranopteris linearis*), sensitivity grass (*Mimosa pudica*) and wire grass (*Sporobolus indicus*, *S. jacquemontii*). The association of species in the grassland vegetation often reflects the soil quality and moisture status, with mission grass being replaced by ferns on poor sites (*talasiga*), whereas reeds appear on sites of better quality.

On ridges, where soils are severely degraded, shallow and often dry, the grassland vegetation consists of less dense stands of bracken fern (*Pteridium esculentum*, *Dicranopteris linearis*) and sparse mission grass with scattered Casuarina trees (*Casuarina equisetifolia*). In areas where the soils are deeper and remain moist for longer periods of time (e.g. gullies and footslopes) the vegetation changes to very dense stands of mission grass and reeds (*Miscanthus floridulus*), associated with guava (*Psidium guajava*), climbers (*Mikania micrantha*, *Passiflora foetida*) and occasional tree ferns (*Cyathea lunalata*).

Table 2.4: *Monthly height estimates of Pennisetum polystachyon grass and the percentage of live grass in Nabou Estate from visual observations made by the author. Mean monthly rainfall amounts at Nabou Headquarters (1974–1991) added for comparison (source: Fiji Meteorological Service).*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation (mm)	265.1	297.3	273.4	165.5	79.98	77.38	61.07	82.19	82.89	114.2	126.3	167.1
Grass height (m)	1.3	1.5	1.7	1.7	1.6	1.4	1.3	1.2	1.0	0.9	0.9	1.2
Live grass (%)	80	100	100	100	90	70	40	30	20	20	30	60

As indicated already, remnants of indigenous forest are found along the stream channels of the larger creeks where moisture is available all year round (Drysdale and Rawaqa, 1987). The vegetation includes native trees (*e.g. Casuarina nodiflora*, *Dysoxylum richii*, *Myristica castaneifolia*, *Alerites moluccana*, *Bischofia javanica*, *Parinaria insularun*, *Inocarpus fagiferus*, *Prema taitensis*, *Intsia bijuga*, *Podocarpus neriifolius*, *Commersonia echinata*, *Alstonia vitiensis*, *Leucenia glauca* and *Cyathea lunulata*) as well as dense undergrowth of grasses, ferns, climbers, weeds (*e.g. Elephantopus mollis*, *Urena lobata*, *Hyptis pectinata*, *Vitex trifolia*, *Dodonea viscosa*, *Decaspermum fracticosum*) and bushes (*e.g. Psidium guajava*, *Piper macgillivrayi*, *Pandanus tectorius*).

Mission grass shows a strong seasonal behaviour with active growth during the wet season (December – April), a flowering period at the onset of the dry season (May – June) and a gradual dying off during the dry season (July – November). Grass height varies from 1.5–1.7 m at the end of the wet season to 0.7–1.0 m at the end of the dry season (Table 2.4). Mission grass is a perennial grass with single plants growing in clumps. Individual plants have a life time of some two years or more, depending on the weather conditions (pers. comm. Mr. T.T. Rawaqa). Biomass production is high during the wet season but decreases rapidly after the onset of the dry season. The annual productivity of mission grass measured at the agricultural research centre near Nacocolevu in the Sigatoka river valley was 6650 kg ha^{-1}, of which 77% was produced in the wet season (December – May). Production of Nadi blue grass (*Dichantium caricosum*), which has only recently been introduced to SW Viti Levu is slightly lower but shows a similar seasonal variation (Table 10.1). Grass production declines rapidly after the flowering period at the onset of the dry season when topsoil moisture levels are not replenished anymore by rainfall. The dying occurs in stages from the tip down to the base of the plant and continues for 2–3 months after which most plants have turned brown. Not all plants in a clumb die at the same time and during the dry season new plants are often produced after infrequent large rainfall events. However, these new plants do not grow very tall and remain hidden between the dead standing crop.

Chapter 3

Description of Study Sites

The Nabou Forest Estate was established in 1974 and comprised 12,382 ha in 1989 (Yabaki, 1989), which decreased to 6659 ha in 1991 (Yabaki, 1991) when logging commenced and plantations damaged by fire and cyclones in the previous years were written off. Seedlings were raised in a nursery at Nabou Estate Headquarters from seeds collected in the seed orchards of Lololo forest near Lautoka until the trees in the Nabou orchard would produce enough seed. Seedlings were raised in polyethylene bags until ready for planting when they had reached a height of 30–40 cm. Planting occurred during the wet season, usually from January until April. No fertilizers were used after the plants had been moved from the nursery. Tree spacing varied between years, ranging from $3 * 3$ m to $2 * 3$ m. Weeding was carried out in the dry seasons during the first two years after planting, until the trees emerged above the grass. No further treatments were applied until harvesting at the end of the rotation, although propping was done to salvage young trees suffering from wind lean after the passage of cyclones (pers. comm. Mr. T.T. Rawaqa, FPL).

3.1 Nabou Grassland

A representative grassland area of about 20 ha (17° 57'S, 177° 19'E, elevation 91 m a.s.l.) was found about 100 m SW of the Fiji Pine Limited Nabou Estate headquarters. As it concerned communal land permission to conduct research had to be obtained from the land owners and this was granted by March 1991. The research plot (0.01 ha) was located on a flat piece of land adjacent to the Kubuna river valley (see Figure 2.2). The topography of the surrounding area was undulating.

The vegetation was well developed and consisted almost entirely of mission grass (*Pennisetum polystachyon*) with some sensitivity grass (*Mimosa pudica*), wire grass (*Sporobolus Indicus*) and bracken fern (*Dicranopteris linearis*). The vegetation was dense as the area had not been burned for several years. Details on biomass *etc.* are given in Chapter 10.

The mineralogical composition of the parent rock was optically determined from thin sections prepared at FES-VUA from a sample collected in the Kubuna river valley. The rock consisted for a large part of well-developed plagioclase (andesine) phenokrists and quartz in a ground mass of plagioclase with traces of K-feldspar and apatite. The abundance of phenokrists indicated that the rock was either formed in a shallow dike or in a thick lava flow (slow cooling). Some 3% of the rock consisted of heavy minerals. Brown hornblende (amphibole) was surrounded by augite (clinopyroxene) and carbonate indicating that a rapid decrease in the water vapour pressure had occurred during the formation of the rock. The sample contained traces of pyrite and some chlorite (due to weathering?). The mineralogical composition indicated that the rock had been deposited in a continental environment and the rock was classified as part of a dacite lava flow or dike (H. Helmers MSc, pers. comm.).

The soil was derived by *in situ* weathering of the parent rock. A profile (GSP1) was described in a soil pit down to a depth of 65 cm in May 1991 according to the FAO Guidelines for Soil Profile Description (1977). Information on soil characteristics deeper in the profile and on the bulk density was obtained from soil samples collected during installation of two capacitance soil moisture probe access tubes (Appendix 24). The soil was classified as an Udic Argiustoll (AID-USDA, 1983). It consisted of a granular brownish black A-horizon underlain by more massive, dark reddish brown B- and C-horizons. Grass roots were found down to a depth of 88 cm. The soil structure was weak. The soil was covered by a complete 10–20 cm thick litter layer, dominated by litter from *Pennisetum polystachyon.* No stones were found on the soil surface. A description of the soil profile is given below along with basic physical and chemical characteristics. Further details are given in Chapter 4.

Soil Profile GSP1

A_1 0–27 cm; Brownish black (7.5 YR 3/2 m, 7.5 YR 4/3 d) clay loam (clay 33%, silt 32%, sand 35%); medium granular; non sticky; non plastic; friable; common fine pores; few strongly weathered rock fragments (1–4 mm); many fine roots; porosity 47%; available moisture for plants 16%; pH= 5.26; pH_{KCl}= 4.80; LOI= 8.2%; %N= 0.14%; %C= 1.53%; gradual and wavy transition to

B_1 27–48 cm; Dark reddish brown (5 YR 3/6 m, 5 YR 5/6 d) clay (clay 46%, silt 27%, sand 27%); medium subangular blocky, non sticky; non plastic; very firm; few strongly weathered rock fragments; frequent small (<2 mm), soft, black spherical ferric-manganese nodules (<2 mm); many fine roots; porosity 40%; available moisture for plants 12%; pH= 5.31; pH_{KCl}= 4.90; LOI= 6.7%, %N= 0.06%; %C= 0.31%; gradual transition to

C_1 48–88 cm; Reddish brown (5 YR 4/8 m, 5 YR 5/6 d) clay (clay 49%, silt 26%, sand 25%); very few fine roots; frequent small (<2 mm), hard, black spherical ferric-manganese nodules; porosity 37%; available moisture for plants 8%; pH= 5.22; pH_{KCl}= 4.91; LOI= 5.9%; %N= 0.07%; %C= 0.43%; diffuse transition to

C_2 88–124 cm; Dark reddish brown (5 YR 3/6 m, 5 YR 5/6 d) clay; non sticky, non plastic, very firm; frequent small (<6 mm), hard, black ferric-manganese nodules; no roots; diffuse transition to

IIC_3 124 cm+; Bright reddish brown (5 YR 5/8 m, 7.5 YR 6/8 d) clay; non sticky, non plastic; very firm; frequent small (<9 mm), hard, black ferric-manganese nodules; no roots;

3.2 Tulasewa Forest

The Tulasewa forest plot (0.25 ha) was situated in a six-year-old pine forest (January 1990) within Fiji Pine Ltd's planning unit PU 20–2 (18°00'S, 177°27'E, 116 m a.s.l.)

along the Marika road, about 5 km North of Tulasewa village (Figure 2.2). Figure 3.1 shows the topographical features of the surrounding area and the plot location. The

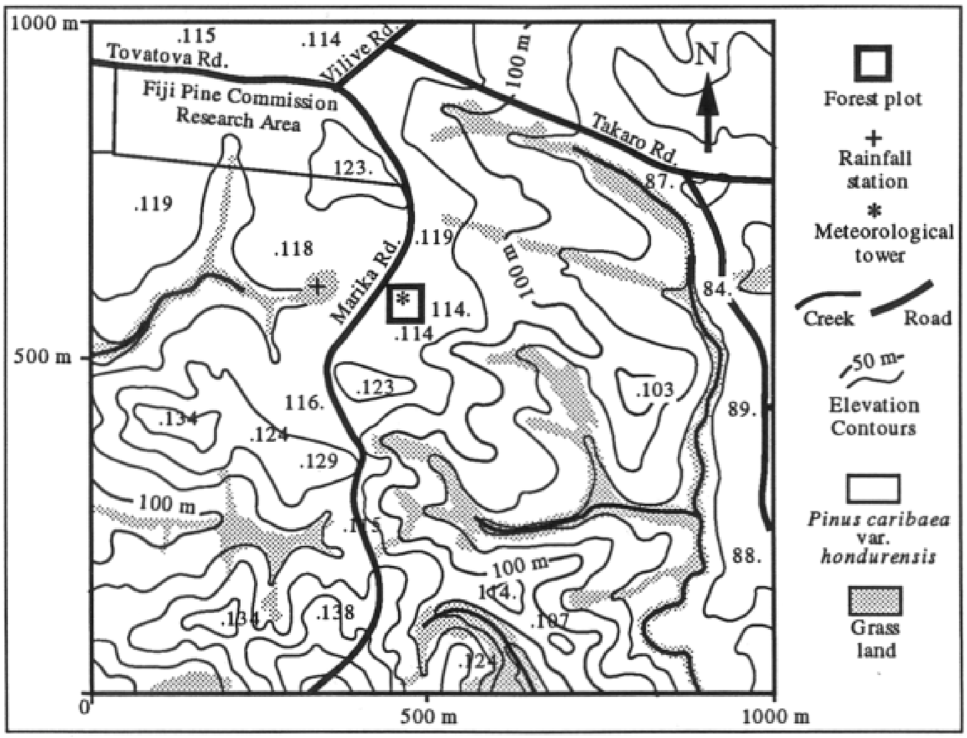


Figure 3.1: *Topographic map of the Tulasewa forest area.*

research site itself was relatively flat and sloped gently towards the SE. The topography of the surrounding area was undulating.

PU 20-2 had been converted from grassland to pine forest (*Pinus caribaea* Morelet var. *hondurensis* Barr. and Golf.) in 1980. However, the forest was destroyed by cyclone Oscar in 1983 and the area was burned before replanting in 1984. The seeds were obtained from pines growing in the seed orchard of Lololo Forest Estate and seedlings were raised in the nursery of the Nabou Forest Estate using local soil. The seedlot number had not been recorded. The forest was planted at a spacing of 3*3 m resulting in an initial stem density of 1111 trees ha^{-1}. At the start of the study in January 1990 the stem density was 825 trees ha^{-1} of which 49 trees ha^{-1} had been planted in 1980, and the rest in 1984. None of the trees planted in 1984 showed any cyclone damage. Cyclone Sina severely damaged the stand in November 1990, reducing the stocking to 491 stems ha^{-1}, of which 18% showed severe cyclone damage (wind lean, stem snap, top damage), whereas the surviving trees were largely defoliated. The average diameter at breast height (*Dbhob*) was 0.156 m and the height of the trees averaged 11.6 m at the start of the study. The leaf area index (LAI) was 3.7 m^2 m^{-2} in July 1990 but had decreased to 1.5 m^2 m^{-2} in July 1991 as a result of cyclone damage. The basal area was 18.1 m^2 ha^{-1} in January 1990 with a current annual increase (CAI) of 3.9 m^2 ha^{-1} yr^{-1} and a mean annual increase (MAI) of 3.0 m^2 ha^{-1} yr^{-1}. Cyclone damage had reduced the basal area to 14.2 m^2 ha^{-1} by September 1991. More details on forest biomass will be presented in Section 11.3.5.

The site index is a measure of forest quality based on the dominant height of the trees in a stand (Ford-Robertson, 1971) and increases with the quality of the site. Site index tables have been prepared for the forests in Fiji (Heuch, 1992). The site index ranges from 10 for poor quality sites to 22 for high quality sites with an areal average of 18 for Nabou forest. The mean top diameter and mean top height (*i.e.* mean diameter and height of 100 trees with the largest diameter per hectare) at Tulasewa were 0.224(±0.012) m and 13.9(±1.1) m (n=31) respectively, resulting in a site index of 22. This compared well with data from the adjacent 0.04 ha permanent sample plot from the Fiji Pine Ltd. (pers. comm. Dr. J.H.R. Heuch).

The undergrowth consisted for some 65% of *Pennisetum polystachyon* which grew in dense stands up to a height of 2–2.5 m during the wet season. Patches of bracken fern (*Dicranopteris linearis*) covered another 20% of the area whereas the remaining 15% was covered by various other species given in Table 3.1 (Beekman, 1992). The vegetation in small moist depressions was dominated by mile-a-minute (*Mikania micrantha*), tobacco weed (*Elephantopus mollis*) and mission grass. High groundwater levels during the wet season prevented pines from growing in these areas.

Rock fragments were collected within the plot at a depth of 60 cm below the soil surface, as well as in the bank of a creek east of the study area. The rock fragments collected within the plot consisted mainly of oriented plagioclase phenokrists (flow structure) in a matrix of clay minerals (*e.g.* smectite) and some apatite. The presence of dark minerals was confined to traces of pyroxene. Some of the pyroxene had been replaced by quartz (high temperature variety). However, the presence of smectites indicated that alteration of minerals had occurred at low temperatures. Limonite had formed in small cracks as a result of weathering. The rock had probably been part of a trachytic lava flow and was classified as a leuco-dacite (Mr. H. Helmers MSc, pers. comm.).

The rock sample collected from the river bank consisted of plagioclase phenokrists (50%) in a fine-grained matrix of plagioclase and pyroxene. Some orthopyroxene (Ca-poor, *e.g.* olivine) and clinopyroxene (Ca-rich) phenokrists, intergrown with magnetite ore were present. Flow structures were observed along the phenokrists. The sample was classified as a tholeiitic basalt (H. Helmers MSc, pers. comm.). As some sandstone fragments were also found within the plot the parent rock may have been a breccia containing fragments of volcanic rock and sandstones. The individual rocks in this breccia most likely belonged to the Tari formation in the Wainimala group (Section 2.2).

As the site was situated close to an area where spacing trials were conducted by the Fiji Pine Ltd. the soil had been disked locally before planting. This showed up as long linear depressions (±20 cm deep and 1 m apart) in some parts of the plot. Surface sheet erosion had been responsible for the local removal of the A-horizon and flintstone fragments (1–5 cm) were commonly found at the soil surface and within the A-horizon (colluvium?). As a result drainage, soil depth, colour, structure and bulk density varied considerably in space. Soil depth ranged from less than 0.8 m to about 1.8 m. The soil was classified as a Udic Haplustoll (AID-USDA, 1983). The structure was weak. Roots were observed throughout the depth of the profile. The soil was generally well drained, although blackish poorly drained soils (nigrescent soils, vertisols) were observed by the author in the area where the rain gauges had been installed (Figure 3.1). A description of an undisturbed soil profile (ASP1), made in a soil pit

Table 3.1: *Undergrowth species in the Tulasewa forest plot.*

Low vegetation

English	**Fijian**	**Latin**
Mission grass	Buinimanipusi	*Pennisetum polystachyon*
Seed grass	Qase	*Chrysopogon aciculatus*
Sensitive grass	Co gadrogadro	*Mimosa pudica*
Wire grass		*Sporobolus indicus*
	Gi	*Imperata cylindrica*
Bracken fern	Qato moce	*Dicranopteris linearis*
Bracken fern	Karuka	*Pteridium aqualinium*
Tobacco weed	Tavako ni veikau	*Elephantopus mollis*
Hibiscus burr	Qatima	*Urena lobata*
Mint weed	Tamoli ni vavalagi	*Hyptis pectinata*
Mile a minute	Wa bosucu	*Mikania micrantha*
Wild passion fruit	Karanidila ni veikau	*Passiflora foetida*
	Vulokaka	*Vitex trifolia*
	Kura	*Morinda citrifolia*
	Nuqanuqa	*Decaspermum fracticosum*
	Usi	*Dodonea viscosa*

Small trees and bushes

English	**Fijian**	**Latin**
	Yaro	*Prema taitensis*
	Sama	*Commersonia achinata*
Casuarina	Nokonoko	*Casuarina equisetifolia*
Guava	Quwawa	*Psidium guajava*
Pandana	Vadra	*Pandanus tectorius*
	Masimasi	*Ficus fulvo-pilosa*
	Yaqoyaqona	*Piper macgillivrayi*

in June 1990, is given below along with basic physical and chemical characteristics. Further details are given in Chapter 4. The pit was dug down to a depth of 1.55 m and faced eastwards with a slope of about 3°. The soil was completely covered by a 7–15 cm thick litter layer, which consisted mainly of dead grass and pine needles. Few angular quartz fragments (flintstones, <4 cm) were present at the soil surface.

Soil Profile ASP1

A_1 0–10/14 cm; Brownish black (10 YR 2/1.5 m, 10 YR 4/3 d) silty clay; medium granular to fine blocky; slightly sticky; non plastic; friable to slightly firm; many fine pores; common roots of all sizes; porosity 62%; available moisture for plants 21%; pH= 5.51; pH_{KCl}= 4.24; LOI= 13.0%; clear and wavy transition to

A_3 12-20/24 cm; Brownish black (10 YR 3/2 m, 10 YR 4/3 d) to brown (10 YR 3/4 m, 10 YR 5/6 d) silty clay; fine to medium angular blocky, slightly sticky; non plastic; firm; few small angular quartz gravel particles (5 mm); common pores; common roots of all sizes; porosity 56%; available moisture for plants 14%; pH= 5.22; pH_{KCl}= 4.16; LOI= 12.1%; clear but irregular transition to

IIC 22-87/95 cm; Reddish brown (5 YR 4/8 m, 7.5 YR 6/6 d) silty clay; coarse angular blocky; friable to slightly firm; sticky; common pores; few to common fine and medium roots; material consists of rotten rock that can be crushed to pseudo sand; A3 material deposited along former root channels; porosity 64%; available moisture for plants 23%; pH= 5.28; pH_{KCl}= 4.13; LOI= 10.2%; abrupt but irregular transition to

IIIC 91-155+ cm; Bright yellowish brown (10 YR 6/8 m, 2.5 Y 8/6 d) to yellowish brown (10 YR 8/3 m, 2.5 Y 8/6 d) strongly weathered silt loam; very firm; slightly sticky, non plastic; common fine to very fine root channels with 5 mm of bleached, pale yellow (7.5 YR 8/3 m) material around them; few fine to medium pine roots; common thin (1-2 mm) black bands (Mn deposited on fracture faces in rotten rock?); porosity 62%; available moisture for plants 24%; pH= 5.67; pH_{KCl}= 4.16; LOI= 9.4%;

The A_1-horizon was directly underlain by the IIIC horizon in parts of the plot where the soil was shallow, whereas the IIC horizon was exposed on the surface in other parts of the plot.

3.3 Korokula Forest

The Korokula forest plot (17°59'S, 117°17'E) was situated east of Korokula village at an altitude of 47 m a.s.l. at a distance from the sea of 2.5 km (Figure 2.2). A 0.2 ha plot (40*50 m) was instrumented in Fiji Pine Ltd. planning unit 9 stand 5 (PU 9–5). The plot was situated on the southwestern slope of a low ridge which formed part of the northern toe slope of the east–west stretching Kalaka ridge (163 m). A map of the area surrounding the forest plot is shown in Figure 3.2. The plot was located in rolling terrain which gradually changed to steeply dissected land higher on the slopes of the Kalaka ridge and to undulating in the river valley.

The grassland vegetation had been converted to pine forest in 1979 and the trees were 11 years old in January 1990. The forest had not been burned at any time during its growth. The seeds were obtained from pines growing in the seed orchard of Lololo Forest Estate and seedlings were raised in the nursery of the Nabou Forest

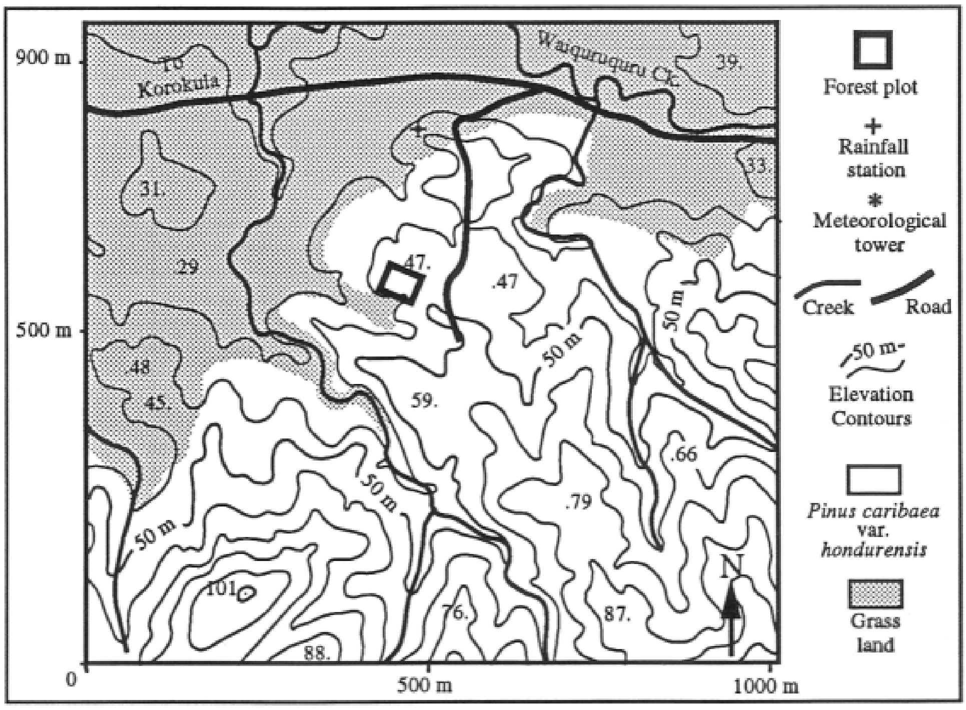


Figure 3.2: *Topographic map of the Korokula forest area.*

Estate using local soil. The seedlot number was 0577-F. The trees were planted at a spacing of 2*3 m resulting in an initial density of 1667 stems ha^{-1}. However, the actual stocking was 822 stems ha^{-1} in January 1990, of which 15% showed cyclone damage ranging from wind lean to multileadering as a reaction to earlier stem snap and top damage. Cyclone Sina (November 1990) further reduced stand density to 789 stems ha^{-1} and defoliated the surviving trees for a large part. The average *Dbhob* and tree height at the start of the study were 0.204 m and 14.7 m respectively. Pre- and post-cyclone LAI's were 4.0 m^2 m^{-2} and 3.1 m^2 m^{-2}, respectively. The basal area was 27.5 m^2 ha^{-1} in January 1990 with a CAI of 2.1 m^2 $ha^{-1}year^{-1}$ and an MAI of 2.5 m^2 ha^{-1} yr^{-1}. The basal area had increased to 28.2 m^2 ha^{-1} in September 1991. The forest in the plot was relatively healthy and well stocked as compared to the surrounding forest. More details are provided in Section 11.3.5.

The mean top diameter and height were 0.262($\pm$0.013) m and 16.5($\pm$0.9) m (n=12) respectively, resulting in a site index of 14. An even lower site index of 10 was found for a nearby 0.04 ha permanent sample plot from Fiji Pine Ltd. (pers. comm. Dr J.H.R. Heuch).

The undergrowth vegetation was much less dense than that at Tulasewa forest and consisted mainly of mission grass (*Pennisetum polystachyon*), blue rats tail (*Stachys tarpheta jamaicensis*, mint weed (*Hyptis ectinata*), some climbers (*e.g. Micania micrantha*, *Passiflora foetida*) and guava bushes (*Psidium guajava*).

Two rock samples were collected, the first in the area adjacent to the forest plot and the second within the forest plot. The first sample consisted of plagioclase phenokrists (15–20%), aligned in a fine matrix of plagioclase and some clinopyroxene (*e.g.* augite) and apatite. Some of the phenokrists had been altered to epidote. Flow structures were observed along the phenokrists, which were present during deposition. The amount of quartz in the sample was negligible and this rock sample was classified as part of an andesitic lava flow (H. Helmers MSc, pers. comm.).

The second sample also consisted of plagioclase phenokrists, which had partly been altered to epidote and clay minerals (*e.g.* smectite). The sample contained elongated vesicles which were filled with secondary quartz and low temperature clay minerals. The matrix consisted of fine plagioclase crystals aligned with the vesicles (flow structures) and was free of quartz. This rock sample was classified as part of an andesite lava, which had been altered to a dacite by deposition of quartz in the vesicles (H. Helmers MSc, Pers. comm.). The parent rock at Korokula clearly belonged to the Tari formation (Kalaka dacite) in the Wainimala group and was very similar to that found in the northern part of the Oleolega catchment (Section 3.5).

The soil was classified as a Udic Haplustoll (AID-USDA, 1983) and was derived by *in situ* weathering of the dacite. The soil profile consisted of a brownish black, sandy topsoil underlain by a brown clayey subsoil. Soil depth varied considerably, ranging from 0.25–0.45 m to 0.7–1.1 m within the plot area. Thin soils were mainly found on the top of the ridge but occurred locally on eroded slopes as well. The soil structure was weak. The soil was well drained.

A soil pit located on a gentle slope within the plot (N144E, 7°) about 10 m from the valley, was dug down to a depth of 0.9 m. A description of the profile (BSP1) is given below. The soil surface was completely covered by a 7 cm thick litter layer, of which the upper 2–3 cm consisted of fresh pine needles (L-layer) and the lower 3–4 cm of partly decomposed needles (F-layer). The transition to the mineral soil was sharp and some gravel was observed at the surface. Surface sheet erosion had resulted in the local dissapearance of the A-horizon, but the A-horizon was present at the site of the soil pit.

Soil Profile BSP1

A_1 0-18 cm; Brownish black (10 YR 3/3 m, 10 YR 5/2 d) sandy loam; medium granular; non sticky; non plastic; very friable; many fine pores; common roots of all sizes; few strongly weathered rock fragments (gravel, 10 YR 5/6 m) present at the soil surface and within the horizon; porosity 48%; available moisture for plants 20%; pH= 5.67; pH_{KCl}= 4.36; LOI= 5.6%; gradual and wavy transition to

A_2 18–30/40 cm; Brownish black (10 YR 3/4 m, 2.5 Y 6/3 d) sandy loam; fine to medium granular, non sticky; non plastic; slightly firm; few small gravel particles; common (bio)pores; common roots of all sizes; porosity 40%; available moisture for plants 16%; pH= 6.01; pH_{KCl}= 4.35; LOI= 3.2%; irregular and wavy transition to

B 30/40–72 cm; Brown (7.5 YR 4/4 m, 10 YR 6/6 d) clay loam; fine to medium angular prismatic with cutans on prism faces; slightly sticky; slightly plastic; very firm; common pores (no biopores) and cracks (1 mm); common fine to medium roots; porosity 54%; available moisture for plants 15%; pH= 6.65; pH_{KCl}= 4.47; LOI= 7.4%; gradual and straight transition to

C 72–90 cm; Brown (5 YR 4/8 m, 10 YR 7/6 d) altered rock silt loam; very firm; slightly sticky, non plastic; few fine to medium pine roots; few small pores; no cracks; common thin (1-2 mm) black bands (Mn, Fe deposited on fracture faces in rotten rock); common mottles (10 YR 7/6 m); porosity 52%; available moisture for plants 20%; pH= 6.54; pH_{KCl}= 4.12. gradual transition to

R 90 cm+ Olive yellow to grayish olive (5 Y 6/3 m, 7.5 Y 7/2 d) strongly weathered dacite; thin (1 mm) black bands (Mn, Fe) in fractures.

3.4 Koromani Forest

The Koromani forest plot (18°00'S, 177°18'E) and the site of the micro-meteorological tower were situated in a mature pine forest near Koromani to the NE of Kubuna village (Figure 2.2). A 0.25 ha plot was instrumented on the north facing slope of a low ridge (82 m a.s.l.) in Fiji Pine Ltd. planning unit 9 stand 4 (PU 9–4). The tower was erected about 100 m North of the forest plot. The topography of the area, the location of the plot and that of the meteorological tower are shown in Figure 3.3. The topography of the area was rolling, gradually changing to steeply dissected further to the north.

The pine forest had been planted on grassland in 1975 and had never been burned. The seeds were obtained from pines growing in the seed orchard of Lololo Forest Estate and seedlings were raised in the nursery of the Nabou Forest Estate using local soil. The seedlot number had not been recorded. The trees were planted at a spacing of 3∗3 m resulting in a initial stocking of 1111 trees ha^{-1}. The actual density was 621 trees ha^{-1} in February 1990 due to natural thinning by cyclones over the years. Thirty five percent of the standing crop showed cyclone damage, ranging from wind lean to multileadering. The average *Dbhob* and height at the start of the study were 0.249 m and 17.5 m respectively. The pre-cyclone LAI was 4.0 m^2 m^{-2}. The LAI had been reduced to 3.1 m^2 m^{-2} in July 1991, 8 months after defoliation by cyclone Sina (and subsequent regrowth). The basal area was 31.6 m^2 ha^{-1} in January 1990 with a CAI of 1.7 m^2 $ha^{-1}yr^{-1}$ and an MAI of 2.1 m^2 ha^{-1} yr^{-1}. A value of 33.5 m^2 ha^{-1} was measured in September 1991. The forest in the plot and that surrounding the meteorological tower were relatively well stocked as compared to the surrounding forest which showed much more cyclone damage. More details will be presented in Section 11.3.5.

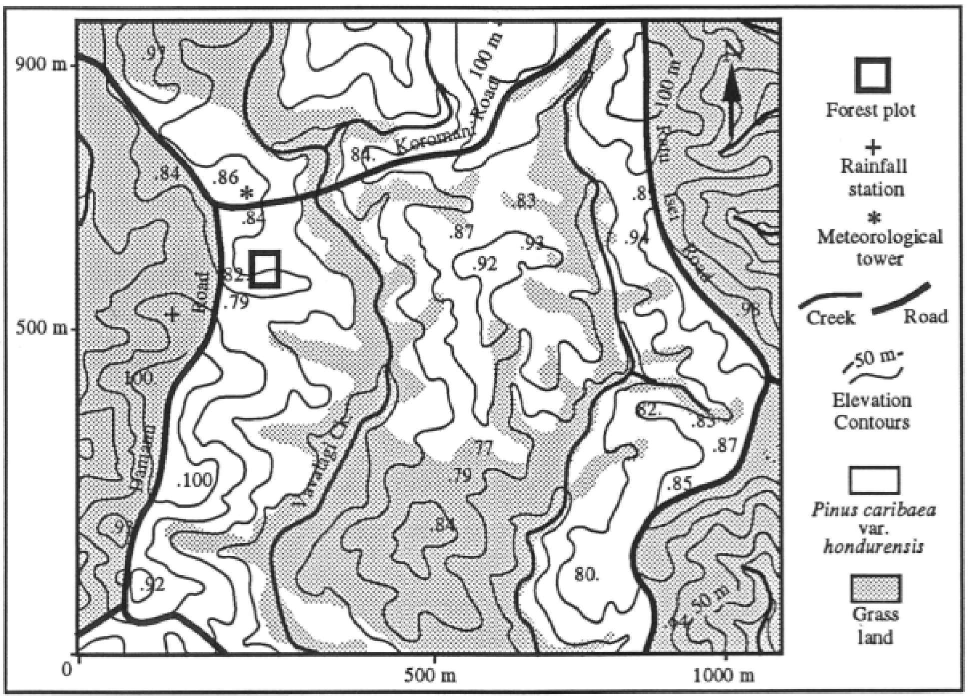


Figure 3.3: *Topographic map of the Koromani forest area.*

The mean top diameter and height were 0.338(±0.043) m and 19.9(±2.2) m (n=16) respectively, resulting in a site index of 14. A site index of 10 was found for an adjacent 0.04 ha permanent sample plot (PSP) from Fiji Pine Ltd. (pers. comm. Dr. J.H.R. Heuch). However, this PSP had been established on a different soil type, which was somewhat similar to that at Korokula forest. The variation in site index therefore adequately reflected differences in growth as a result of the variation in the soils. Harvesting started at age 16.8 in November 1991.

A listing of the undergrowth species in Koromani forest is given in Table 3.2. The undergrowth vegetation in Koromani forest consisted for 38% of grasses (*e.g. Pennisetum polystachyon, Imperata cylindrica*) associated with climbers (*e.g. Passiflora foetida, Mikania micrantha*, 14%), weeds (*e.g. Elephantopus mollis*, 5%) and guava bushes (*Psidium guajava*, 36%). Young indigenous trees accounted for 6.6% of the undergrowth biomass. Some bracken fern, reeds, few palms and an occasional tree fern were observed within the plot area.

Thin sections were made of two rock samples collected close to the site. The first sample consisted for 80% of plagioclase in a matrix of chlorite (10%), formed around magnetite grains. Some plagioclase had been altered to epidote and both plagioclase and chlorite had been replaced by calcite (5–10%) at a later stage. The calcite could have been transported in groundwater from karstified carbonate banks of

Table 3.2: *Undergrowth species observed in Koromani forest.*

Low vegetation

English	**Fijian**	**Latin**
Mission grass	Buinimanipusi	*Pennisetum polystachyon*
T-grass		
Sensitive grass	Co gadrogadro	*Mimosa pudica*
Wire grass		*Sporobolus indicus*
	Gi	*Imperata cylindrica*
	Malatava	
	Wakadua	
Blue rats tail		*Stachys tarpheta jamaicensis*
Reeds	Gasau	*Miscanthus floridulus*
Bracken fern	Qato moce	*Dicranopteris linearis*
Bracken fern	Karuka	*Pteridium aqualinium*
Tree fern	Balabala	*Cyathea lunulata*
Tobacco weed	Tavako ni veikau	*Elephantopus mollis*
Hibiscus burr	Qatima	*Urena lobata*
Mile a minute	Wa bosucu	*Mikania micrantha*
Wild passion fruit	Karanidila ni veikau	*Passiflora foetida*
Blue berry vine		
Star vine		

Small trees and bushes

English	**Fijian**	**Latin**
	Kaukamea	
	Sama	*Commersonia echinata*
Guava	Quwawa	*Psidium guajava*
Pandana	Vadra	*Pandanus tectorius*

which outcrops had been observed between layers of volcanic rock in the area adjacent to the plot. Secondary quartz formed about 1% of the total mass. The presence of pumpellyite in the sample indicated hydrothermal activity after the deposition of the rock. No flow structures were observed. Some small mineral inclusions indicate that the rock may have been part of a volcanic plug or a crater wall. The rock was classified as an andesite (pers. comm. H. Helmers MSc).

The second sample consisted of large plagioclase phenocrists in a matrix of fine plagioclase crystals, magmatic and post-magmatic amphiboles and some hydrothermally formed pyroxenes. The core of the amphibole crystals had occasionally been altered to chlorite, as well as to biotite (traces). Some sericite had formed within the plagioclase cristals. The size of the phenocrists indicated that the rock had cooled slowly and it may have been part of a dike. The rock was classified as a diabase (pers. comm. Mr. H. Helmers MSc). These rocks typically belong to the Tari formation in the Wainimala arc and matched those found in the southern part of the Oleolega catchment (Section 3.5).

A reddish brown soil was formed by *in situ* weathering of the underlying rock and was classified as a Typic Eutrustox (AID-USDA, 1983). The soil was well drained and the structure weak. More details are given in Chapter 4. A soil pit, located on a midslope position within the plot (N10E, 7°), was dug down to a depth of 1.7 m. A description of the profile (CSP1) is given below. The soil was completely covered by a 7–12 cm thick litter layer, of which the upper 2–3 cm consisted of fresh pine needles (L-layer) and the lower part of partly decomposed needles (F-layer). The transition to the mineral soil was sharp. No stones were found on the soil surface and no evidence of surface sheet erosion was observed within the plot.

Soil Profile CSP1

A$_1$ 0–9/11 cm; Dark reddish brown (5 YR 3/4 m, 7.5 YR 5/4 d) silty clay; medium to course granular; sligtly sticky; non plastic; friable; many fine pores; common roots of all sizes; porosity 51%; available moisture for plants 16%; pH= 4.99; pH_{KCl}= 4.33; LOI= 15.1%; clear and wavy transition to

A$_3$ 10–20 cm; Dark reddish brown (10 YR 3/4 to 3/6 m, 7.5 YR 5/6 d) silty clay; medium angular blocky, slightly sticky; non plastic; friable to slightly firm; many (bio)pores; many roots of all sizes; few fine to medium angular gravel; porosity 52%; available moisture for plants 15%; pH= 5.21; pH_{KCl}= 4.24; LOI= 11.3%; clear and wavy transition to

B 20–90 cm; Reddish brown (2.5 YR 4/8 m, 5 YR 6/8 d) clay; medium to coarse angular blocky; shiny surfaces on peds (cutans?, matrans?) with reddish brown (2.5 YR 4/5 m) colour; sticky; slightly plastic; friable; common fine to medium pores; few fine to medium roots, with a concentration (horizontal direction) between 80 and 90 cm; few small pieces of weathered rock; horizon derived from underlying horizon; pH= 5.09; pH_{KCl}= 4.13; porosity 54%; available moisture for plants 14%; LOI= 11.3%; clear and smooth to wavy transition to

C 90–170+ cm; Reddish brown (2.5 YR 4/8 m, 5 YR 5/8 d) to bright reddish brown (5 YR 5/8 to 4/8 m, 7.5 YR 7/6 d) silty clay; strongly weathered rock; massive yet friable; slightly sticky, slightly plastic; few very fine to medium pine roots; very few small pores; pH= 4.46; pH_{KCl}= 4.01.

3.5 Oleolega Catchment

The Oleolega catchment (18°00'S, 177°21'E) was situated 5 km SE of Nabou station (Figure 2.2). The basin covered a large part of planning unit 10 stand 3 (PU 10-3) which also included the upper part of the Naruku catchment. The areas occupied by the two catchments were 62.9 ha and 33.5 ha, respectively, resulting in a total area of 96.4 ha for PU 10-3. A topographic map of the Oleolega catchment is shown in Figure 3.4. Elevations ranged from 112 m a.s.l. at the basin outlet to 249 m a.s.l. at the highest point. Slopes were moderately steep to very steep, ranging from less than 5° on ridges and in the larger stream valleys to 75° on the slopes of strongly incised valleys and on former landslides faces.

The drainage pattern was dendritic and the main stream was of the 3^{th} order at the basin outlet according to the Strahler classification system. There were 17 first order streams and 5 second order streams (Figure 3.4). The stream frequency (*i.e.* total number of streams per unit area) was high at 36.6 streams km^{-2}, whereas the drainage density (*i.e.* the total stream length per unit area) was relatively low at 3.6 km km^{-2}. The drainage density for the larger catchment area (PU 10–3 and PU 10–5, 242 ha), comprising both the Naruku and Oleolega creeks, was 6.2 km km^{-2}. The drainage density in the Ividamu catchment (PU 10–4, Figure 2.2), the size of which (69.0 ha) was comparable to that of the Oleolega catchment but which had not been planted to pine, was 5.9 km km^{-2}.

Native forest, grasses and reeds growing in the moist riparian zone covered 11.3 ha of the Oleolega catchment and 3.8 ha of the adjacent Naruku catchment. The remaining area of PU 10–3 (81.3 ha) had been planted to pines in early 1975 using a spacing of 3∗3 m (1111 stems ha^{-1}). The reforested area in the Oleolega catchment covered 51.6 ha. The forest showed no fire damage but poor growth was observed on some ridges where soil depth was less than 0.5 m.

Data on the tree size and the structure of the forest in Oleolega catchment were obtained from 81 trees measured at various sample points during the present study (*Dbhob* and damage assesment), and from data (*Dbhob*, *h* and damage assesment) of four Permanent Sample Plots (PSP) of the Fiji Pine Ltd., which were located in the area surrounding the catchment. As the conditions (*e.g.* soils) at these PSPs were comparable to those in the catchment the data obtained in these plots are thought to be representative for those in Oleolega catchment. Three of the four PSPs had been established in 1980 when the forest was 5.5 years old (area: 0.02 ha), whereas the fourth was established in 1990 at age 15.5 (area: 0.04 ha). One of the PSPs established in 1980 (PU 10-5, SP-8) was abandoned after cyclones reduced the stocking from 800 trees ha^{-1} in 1980 to 450 trees ha^{-1} in 1985 and 300 trees ha^{-1} in 1987 of which 30% was severely damaged and had no merchantable value. The two other plots established in 1980 (PU 10-2, Exp. 1753/1 and PU 10-3, Exp. 1751/10) were monitored until 1990 with intermediate measurements in 1985, 1986 and 1987. The PSP established in 1990 (PU 10-5, Exp. 1750/17) covered a relatively well stocked part of the forest and was only measured on that occassion as logging started several months afterwards.

The stocking in the permanent sample plots varied between 250 and 850 trees ha^{-1} in July 1990 with an average of 560 trees ha^{-1} (n= 4), down from an average of 850 trees ha^{-1} (n= 3) in 1980. As only 82% of the catchment area was forested the average stocking amounted to 459 trees ha^{-1} over the whole catchment in 1990. The stocking was further reduced by damage afflicted by cyclone Sina. Before the passage of cyclone Sina in November 1990, some 32% of the trees in the sample plots showed severe cyclone damage and had little or no merchantable value. Damage caused by

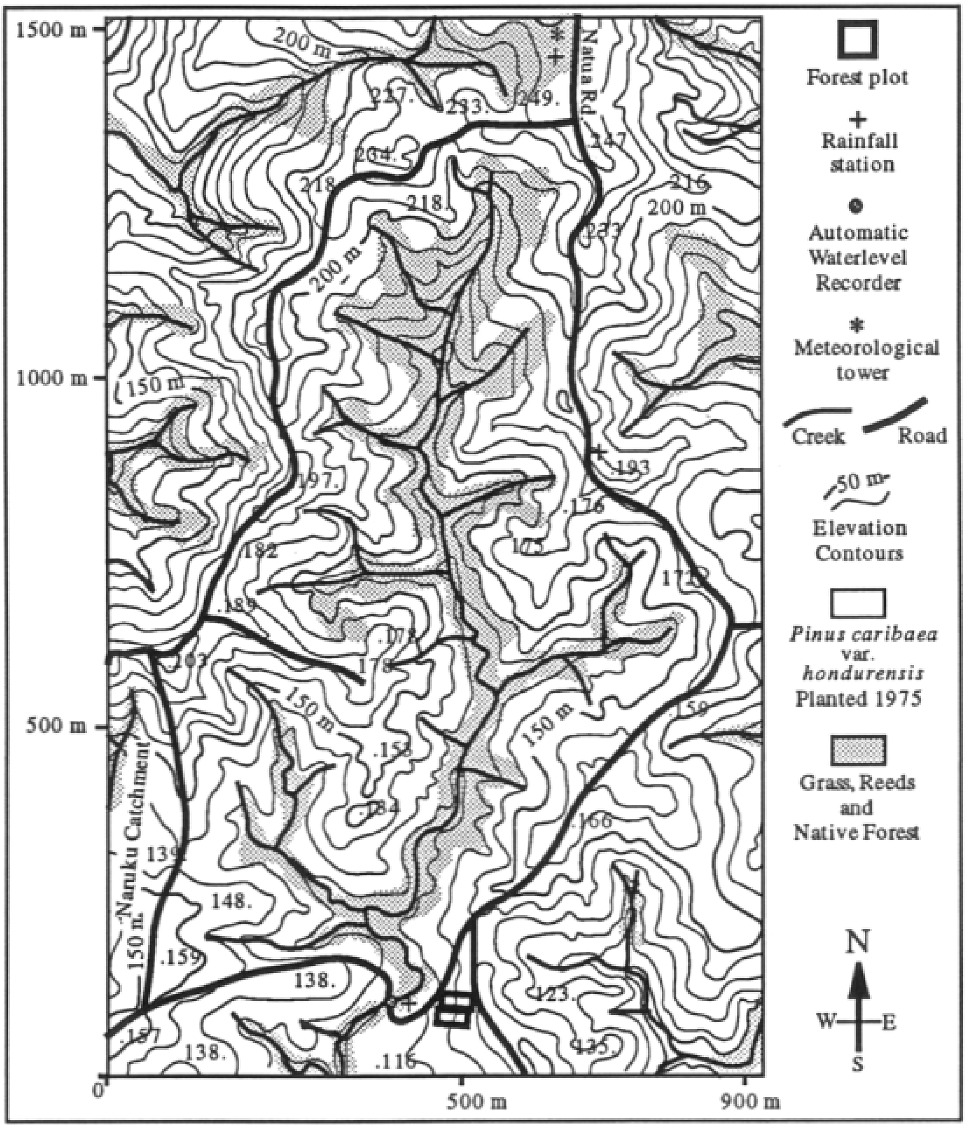


Figure 3.4: *Topographic map of the Oleolega catchment.*

cyclone Sina in 1990 increased this to 42% of the total.

In 1980 the mean *Dbhob* of the trees in the PSPs was 0.129($\pm$0.028) m (n= 51) and the height averaged 11.8($\pm$3.3) m (n= 9). Ten years later averages of 0.251($\pm$0.059) m (n= 144) and 18.3($\pm$3.1) m (n= 41) were obtained for the *Dbhob* and h, respectively, which were not significantly different (α= 0.01) from those observed in Koromani forest (Table 11.1). The crowndepth was measured in the PSP established in 1990 and was 7.2($\pm$2.1) m (n= 13). The basal area was 11.7 m^2 ha^{-1} in 1980 and had increased to 29.3 m^2 ha^{-1} in 1990.

The average *Dbhob* and tree height at the end of 1990 (age 15.8 years) had reached 0.251 m and 18.3 m, respectively. The basal area was 29.3 m^2 ha^{-1} in early 1990 with an MAI of 1.9 m^2 ha^{-1} yr^{-1}. A site index of 10 was assigned to the catchment area by the Fiji Pine Ltd., on the basis of measurements carried out in the permanent sample plots discussed above (Pers. comm. Dr. J.H.R. Heuch).

The undergrowth vegetation on the hillslopes was similar to those in Koromani and Korokula forests. However, the ridges were covered with undergrowth vegetation typical for the *talasiga* areas and consisted for a large part of ferns (*e.g. Dicranopteris linearis, Pteridium esculentum*) with sparse mission grass cover and few Casuarina trees (*Casuarina equisetifolia*).

Soil moisture levels in the riparian zone were too high for the growing of pines and dense stands of reeds (*Miscanthus floridulus*) and mission grass were present along the smaller ephemeral streams whereas native forest covered the area along the larger perennial streams. The species composition of the native forest was typical for the area as described in Section 2.5.

Thin sections were made of eight rock samples, of which seven were collected within the drainage basin. A detailed description of all samples is given in Appendix 23. The parent rock in the northern part of the catchment was classified as a dacite or trachyte lava flow and consisted mainly of plagioclase phenocrists in a matrix of quartz and plagioclase. Columnar jointing was observed in the field. The mineralogical composition was typical for the Kalaka dacites in the Wainimala group and was comparable to that observed in the rock samples collected at Korokula forest (Section 3.3). The parent rock in the southern part of the catchment was classified as a basalt or diabase, with a composition similar to that observed in Koromani forest. The mineralogical composition of the rock and the geographical position suggested that the rock belonged to the Tari formation in the Wainimala group (Section 2.2).

The soils in the catchment were very variable in depth, color and physical and chemical characteristics. However, two major soil groups could be distinguished, both of which were derived by *in situ* weathering of the parent rock (dacite and diabase). Relatively thin (0.2–0.6 m) light grey – yellow – dull orange – yellowish brown soils were found on the ridges and slopes in the northern part of the catchment and were tentatively classified as Udic and Lithic Haplustolls. Some of these soils were roughly comparable to the soil at Korokula forest (Udic Haplustoll). Somewhat deeper (0.6–1.5 m) dull orange – bright reddish brown soils were found on the slopes in the southern part of the catchment overlying the diabase parent rock. The color of soils in the valleys and on relatively flat parts of the area ranged from dull orange to orange. These soils were of slightly finer texture than those formed on dacite and were roughly comparable to those at Koromani forest (Typic Eutrustox) and Nabou grassland (Udic Haplustoll). Poorly drained, dark soils (nigrescent soils rich in Fe and Mn?, Vertisols) were observed locally at exfiltration zones. The structure of both soil types was weak and the profiles consisted generally of a granular topsoil (0–0.2 m) with many biopores, underlain by a more massive B/C-horizon or rotten rock. The soils on slopes and ridges were well drained. Details on the physical and chemical characteristics are provided in Chapter 4.

Chapter 4

Soil Characteristics of Study Sites

4.1 Introduction

The soil is the medium from which the vegetation obtains most of its nutrients and its support, hence its physical and chemical characteristics are of major importance for the development of the vegetation, but at the same time they are also influenced by it. Plantations established on shallow soils, or on soils of poor stucture with high bulk densities and low infiltration capacities, may be subject to a range of problems restricting wood production (*e.g.* periodic water stress, impeded root development, erosion). Periodic water stress may be a growth limiting factor on excessively drained sandy soils, whereas waterlogging may pose a problem to some species (*e.g. Pinus caribaea*) planted on poorly drained soils. Restricted growth may also occur when the nutrient demands of the forest exceed the capacity of the soil to supply those nutrients, or when certain elements (*e.g.* Al, Mn) reach toxic levels in acid, deeply weathered soils (Sanchez, 1976).

The conversion of old, well established grasslands to plantation forests causes changes in the hydrological and nutrient cycles, and always involves some form of soil disturbance. Three phases can be recognized, in which distinct changes in soil physical and chemical properties may occur as a result of soil disturbance, changes in the composition of the vegetation–litter complex, and changes in the microclimate at the soil surface. The first phase is the initial site preparation and planting phase. The forest is growing towards maturity in the second phase, whereas harvesting of wood and site preparation for the planting of the next rotation occur in the third phase (Evans, 1992).

In Fiji, the initial site preparation practice involves burning of the vegetation – litter complex and the construction of permanent roads (usually on ridges) to provide access for planting crews and for future fire fighting. Some physical deterioration of the soil may occur at this stage due to raindrop impact on the bare soil and the oxidation of soil organic matter. However, periodic burning is a normal feature of these grasslands and the vegetation returns within a few months after the burn so that the soil remains bare for only a short period of time. The burning of the vegetation and litter is likely to improve the soil fertility by the release of nutrients from the ash (Sanchez, 1976). Planting is done manually with little disturbance to the soil and weeding (with cane knives) along the planting rows is the normal practice during the first two years following planting. The weeding residue is left *in situ* as mulch and the nutrients released from it by decomposition may be used by the young pines. As soil disturbance is low during this phase the overall impact of the site preparation burn, planting and weeding on soil physical properties may be considered low, and the chemical properties may be influenced positively.

The second phase involves the growing of the forest until it reaches maturity at the end of a rotation period. During this phase improvements of soil physical properties may be expected due to the development of an extensive and deep rooting system by the forest, as opposed to the shallow root system of limited areal extent of the grass. The higher biological activity in afforested soils will also improve the soil structure by increasing soil organic matter content and by the creation of macropores, which tends to result in lower bulk densities and higher porosities and infiltration capacities (Lal, 1987). Higher infiltration capacities have indeed been observed in topsoils under *Pinus caribaea* plantation forests as compared to those under grasslands in Fiji (Cochrane, 1969; Bayliss-Smith, 1983). Bayliss-Smith (1983) also observed higher porosity, biological activity and lower bulk density and structural instability in the top 10 cm of the soil under 6-year old *Pinus caribaea* forest as compared to those in adjacent *talasiga* grass and fern areas. Latham (1983) found that the impact of reafforestation on soil properties in Fiji remained confined to the topsoil. The increased infiltration capacity of soils under *Pinus caribaea* plantations as compared to those in *talasiga* areas resulted in a reduction of the surface runoff from 60–70% to 5–10% of total rainfall (Cochrane, 1969). The observed effects of afforestation on soil physical properties in the Nabou area will be discussed in Section 15.3.

Whether the fertility of the soil is improved during this phase depends on many factors including the initial soil fertility and capacity to retain nutrients, the intensity of soil disturbance during site preparation (erosion), the length of the rotation, the biomass production and nutrient requirements of the forest, the litter turnover rate, the relative rates of weathering and leaching and the atmospheric nutrient input. Few studies have dealt with the impact on soil fertility of converting degraded grasslands to plantation forests in the tropics. In Brazil, Barros and Brandi (1974) observed that chemical properties had improved eight years after degraded grassland soils had been planted to two hardwood species and *Pinus elliottii*, with the soil under the pine forest showing less improvements than those under the hardwood species. In Nigeria, Iyamabo (1973) observed higher levels of phosphorus and mineral nutrients in the soil under a 7-year old *Pinus caribaea* plantation planted in an area which had previously been under a grass fallow followed by a four-year rotation of *Eucalyptus camaldulensis*. No changes were observed in soil pH, organic matter and nitrogen content. Tosin (1977), on the other hand, documented adverse affects of the conversion of natural forest to *Pinus elliottii* and *Auracaria augustifolia* plantations in Brazil whereas Jamet (1975) reported lower organic matter and base saturation levels and higher acidity in soils after the planting of several pine species on savanna soils. Improvements of soil fertility during the recovery phase in shifting cultivation systems are well documented (*e.g.* Nye and Greenland, 1960) but it remains uncertain if short-rotation man-made forests can improve the soil fertility in the same way as a natural fallow (Lundgren, 1978).

Prevention of wildfires in the plantation forests in Fiji is of major concern and this could lead to improvements in site fertility as nutrients otherwise lost during periodic grassland fires through volatilization (*e.g.* N, C, S) or in overland flow and enhanced leaching (*e.g.* K, Ca, Mg) may now be retained within the ecosystem (Kellman, 1989). Increases in soil organic matter via litter fall and subsequent decomposition during the development phase of the forest, as observed by Nye and Greenland (1960) during the fallow phase of soil under shifting cultivation, may enlarge the nutrient retention capacity of the soil thereby reducing leaching hazards.

The third phase comprises the harvesting of the forest and the preparation of the site for the next rotation. The changes associated with this phase will be described separately in Chapter 15 as part of the Oleolega catchment experiment (and not repeated here).

Physical and chemical characteristics of the grassland soil, and those of the soils in Tulasewa, Korokula and Koromani forests will be presented in the following sections. Comparisons between the grassland and forest soils will be made at the end of this chapter to determine the impact of afforestation in the Nabou area on soil physical and chemical properties.

4.2 Field and Laboratory Procedures

Soil samples were collected from distinct horizons in soil pits at the Nabou grassland site (May 1991), and in the Tulasewa, Korokula and Koromani forest plots (June 1990). Additional samples were collected within 50 cm of the stumps of trees sampled for biomass (March–September 1991) and at 7–9 randomly selected sample points (July–September 1991) in the forest plots. Most samples were therefore collected during the dry season.

Samples for chemical and granulometric analyses were collected according to the following procedure. To account for the spatial heterogeneity at a sample point two holes were augered with a spacing of about 1 m and samples collected from each hole at depths of 0–10 cm, 10–20 cm, 30–40 cm, 50–60 cm, 60–70 cm and at 80–90 cm or 90–100 cm (depending on the depth of the bedrock) were bulked. All samples were packed in plastic bags, air dried and shipped to the FES-VUA in the Netherlands for analysis.

Samples collected from soil pits and around the trees sampled for biomass (topsoil only) were analysed individually to obtain some insight into the spatial heterogeneity within a plot. To reduce the total number of samples to a maximum of eight for each depth interval in each plot, samples of corresponding depths, collected at 3–4 adjacent sample points, were bulked in the laboratory at FES-VUA.

Bulk density profiles for the soils were obtained from samples removed at the installation of the access tubes for the capacitance probe (see Appendix 24). Additional data was obtained from undisturbed soil cores of 100 cm^3 collected for the determination of the hydraulic conductivity and soil moisture characteristics.

Details of sampling locations and the procedures used in the Oleolega catchment are provided in Chapter 15.

Hydraulic conductivity (K_{sat}) was measured on undisturbed soil cores using a permeameter (ICW, The Netherlands). The falling and constant head methods were used for soils of low and high permeability respectively (Kessler and Oosterbaan, 1973). For several samples K_{sat} was determined by both methods, resulting in differences of less than 20% between estimates. The same cores were used to measure soil moisture retention characteristics on a sand box for pF= 0.4–2.0 and on a sand–clay box for pF= 2.3 and pF= 2.7. A pressure membrane extractor (Soil Moisture Equipment

Co., USA) was used to obtain values for pF= 3.5 and 4.2 on separately collected soil aggregates (Stakman, 1973). About 20 g of soil was air dried to obtain the residual moisture content (pF≈ 5.5).

Soil pH was measured in a mixture of 40 ml demineralised water and 16 g air-dry soil. The pH was measured (Section 13.2.3) after the mixture was thoroughly shaken and left to equilibrate for 16 hours. To determine the pH_{KCl}, 1850 mg of KCl was added to the previous mixture, after which it was shaken every 15 minutes and the pH_{KCl} measured after 45 minutes (Jackson, 1958).

Loss on ignition (LOI) was determined by heating 5 g of oven-dry soil (105 °C) at 550 °C for 4 hours after which the loss of weight was determined. At this temperature all organic carbon would have been released as CO_2 whereas dehydration of clay minerals would be minimal (Jackson, 1958).

The particle size distribution was determined for the fine earth fraction (0–2 mm) with a Fritsch laser particle sizer analysette 22 after the following treatment. All organic material was removed by boiling 1 g soil in 10 ml of a 30% H_2O_2 solution. The residue was boiled in 100 ml HCl solution (0.5%) and washed two times with demineralised water. The residue was then boiled in a sodium-diphosphate solution for peptization. The particle size distribution was determined from the output of the Fritsch analyssette using a computer program based on the Mie theory of light scattering (Kuik, 1992). The 1–2 mm fraction was also determined by sieving the samples collected in the soil pits.

The carbon (%C) and nitrogen (%N) contents of the soil were simultaneously determined with a Carlo Erba NA-1500 flash-combustion chromatograph on 20 mg subsamples of dry (70 °C) soil ground in a mortar to a particle size of 30–50 μm. Duplicate measurements were made for the soils from the grassland and forest plots. There was some difficulty in homogenizing the samples and due to the small size of the subsample relatively large differences were sometimes observed between these replications. The absolute error in %N was estimated at 0.009% and that of %C at 0.14%.

The CEC and exchangeable bases (Na, K, Ca, Mg) of samples collected from the soil pits were determined with Ag-thiourea (AgTU, 0.01 N) according to the single-extraction technique proposed by Chhabra *et al.* (1975) and Pleysier and Juo (1980). The results of this method are comparable to those of the conventional ammonium-acetate (NH_4OAc) method (van Reeuwijk, 1987). However, due to problems with the stability of the AgTU complex (pers. comm. Dr. C.A.J. Appelo) this method was not used for the soil samples collected in 1991.

Exchangeable cations are conventionally extracted using a 0.1 M NH_4OAc solution adjusted to a pH of 7 by adding HCl (Landon, 1984; van Reeuwijk, 1987). However, the NH_4OAc method alters the pH, thereby affecting the exchange capacity of the soil, and resulting in less realistic values of exchangeable bases and CEC in acid soils (Stumm and Morgan, 1981). It also excludes the determination of exchangeable NH_4. The advantages of the $SrCl_2$ extraction method described below (pers. comm. Dr. C.A.J. Appelo) include the possibility of measuring amounts of exchangeable NH_4, whereas the decrease in soil pH due to the exchange of protons for Sr^{2+} ions may also occur under natural conditions (*e.g.* after fertilizing or high salt inputs).

Exchangeable cations and NO_3 were extracted from 4 g subsamples of crushed (particle size <2 mm), dry (60 °C) soil. The extraction was done in three steps. Each step consisted of adding 10 ml of $SrCl_2$ solution (50 meq l^{-1}) to the soil after which the mixture was shaken for one hour, centrifuged at 3000 rpm for 15 minutes and the clear extract collected in a glass storage vessel. The total extract was weighed (after

Table 4.1: *Linear regression constants (a, b) and statistics relating concentrations of exchangeable Na, K, Ca and Mg as determined with the $SrCl_2$ method to those of the NH_4OAc method and* vice versa. *The ranges for which the constants apply are given as well.*

Species	a	SE	b	SE	CD	n	F-ratio	Range [meq/100 g soil] SrCl2	NH4Ac
Independent SrCl2 method, dependent NH4Ac method									
Na	1.726	0.558	0.012	0.036	0.66	7	3.09	0.02-0.09	0.07-0.22
K	2.988	0.602	-0.009	0.020	0.83	7	4.96	0.02-0.06	0.04-0.18
Ca	1.900	0.364	0.155	0.297	0.85	7	5.22	0.10-0.92	0.10-1.92
Mg	1.880	0.293	0.044	1.009	0.89	7	6.42	0.20-3.84	0.15-7.20
Independent NH4Ac method, dependent SrCl2 method									
Na	0.380	0.123	0.016	0.017	0.66	7	3.09	0.02-0.09	0.07-0.22
K	0.278	0.056	0.010	0.006	0.83	7	4.96	0.02-0.06	0.04-0.18
Ca	0.445	0.085	0.001	0.144	0.85	7	5.24	0.10-0.92	0.10-1.92
Mg	0.475	0.074	0.144	0.507	0.89	7	6.42	0.20-3.84	0.15-7.20

filtering using a 0.45 μm Millipore filter when necessary) and the concentrations of Na, K, Ca, Mg, NH_4 and NO_3 were determined following the procedures given for the analysis of water samples (Section 13.2.3). Duplicate measurements were made for each soil sample and the average concentrations were then converted to meq 100 g^{-1} dry soil.

To compare the $SrCl_2$ method to the more conventional method of extraction with NH_4OAc, amounts of exchangeable Na, K, Mg and Ca were determined with both methods on seven soil samples. Linear regression analysis was used to obtain expressions of the form ($Y = aX + b$) relating the results of the NH_4OAc method of extraction (X) to those of the $SrCl_2$ method (Y) and *vice versa*. The regression constants (a, b), various statistical parameters and the ranges of the exchangeable species for both methods are shown in Table 4.1. Significant relationships were found for K, Ca and Mg, but not for Na, as indicated by the low F-ratio. The values obtained with the $SrCl_2$ method were much lower than those obtained with the NH_4OAc method, amounting to 38%, 50%, 53% and 68% of those measured with the NH_4OAc method for K, Ca, Na and Mg respectively.

As the results of the AgTU extraction method are comparable to those of the NH_4OAc method (van Reeuwijk, 1987), the values for exchangeable bases obtained with the AgTU method for samples collected from the soil pits were converted to those which would have been obtained with the $SrCl_2$ extraction method using the appropriate regression coefficients given in Table 4.1.

The determination of 'Available' P is troublesome as the amounts of P extracted depend on the extraction method, as well as on the form of the P components in the soil. As such a method may perform well in one type of soil, whereas results are poor for other soil types. The appropriate method of extraction should therefore be obtained by trial and error for each new situation (Dr. V.J.G. Houba, pers. comm.). In the present study 'Available' P was determined using the two methods discussed below. The first method involved the extraction of 'available' P from 5 g subsamples of crushed (particle size <2 mm), dry (60 °C) soil in 12.5 ml of a Ca-lactate (60 g l^{-1}) and HCl (16.8 ml l^{-1} HCl, 37%) solution (Chen *et al.*, 1956; Steubing and Fangmeier, 1992). The mixture was shaken for one hour and left to equilibrate for 18 hours. The extract was filtered and analysed for PO_4 following the procedures given for water samples in Section 13.2.3. This method was designed to extract the calcium phosphates and part of the Fe-P and Al-P forms due to complexation with lactic acid (Houba *et al.*, 1989). The second method involved the extraction of 'Available' P in samples collected from the soil pits only following the Bray P-II extraction method (Bray and Kurtz, 1945). This method uses an extraction solution composed of HCL (0.025N) and NH_4F (0.03N) and is more agressive than the Ca-Lactate method as the extraction occurs at a lower pH. The combination of HCl and NH_4F is designed to remove easily soluble P forms, largely Ca phosphates (HCl), and a portion of the Al and Fe phosphates by complex ion formation with NH_4F and is most succesful in acid soils (Olsen and Sommers, 1982).

The bulk chemical compositions of rock and soil samples collected from the various horizons in soil pits in Tulasewa, Korokula and Koromani forests were determined on samples of 0.25 g ground dry material. The material was digested in a solution consisting of 10 ml HF (48%) and 10 ml of a mixture (1:2) of HNO_3 (65%) and $HClO_4$ (70%). The digest was dried and the residual salts were solved in a 2% HNO_3 solution and analysed for Si, Ti, Al, Fe, Mn, Mg, Ca, Na and K on the ICP following the procedures given for water samples (Section 13.2.3). Alternatively, rock samples collected from the sites were analysed on a mass spectrometer (Philips PW 1404/10, Sc-anode X-ray tube operating at 50 kV and 50 mA) after samples had been fused with Li-metaborate.

4.3 Soil Physical Characteristics

4.3.1 Soil Texture

The texture of the soil is one of several factors (*e.g.* structure, humus content, particle shape) determining soil hydraulic conductivity, soil moisture retention characteristics and the sensitivity of the soil to rainsplash and erosion (Sanchez, 1976; Morgan, 1986). The hydraulic conductivity is generally high in coarse textured soils (sands) and decreases by several orders in silty and clayey soils, unless stable aggregates are formed. The impact of a conversion from grassland to forest on the soil hydraulic conductivity can therefore only be assessed for soils of comparable texture. In general, porosity varies from some 30% in sands to over 60% in clayey soils. The water holding capacity of a soil generally increases with the proportion of silt and clay and the vegetation on fine grained soils is therefore less likely to suffer from water stress than that on coarser grained soils. Coarser soils, on the other hand may be less sensitive to erosion due to their higher infiltration capacities (Morgan, 1986).

The texture of the fine earth fraction was described in the field following the FAO Guidelines for soil profile description (FAO, 1977), which uses the textural classification of the U.S.D.A. Soil Taxonomy (USDA, 1975). Therefore clay, silt and sand fractions refer to particle sizes of <0.002 mm, 0.002–0.05 mm and 0.05–2 mm, respectively. The sand fraction was further subdivided into coarse sand (0.25–2 mm) and very fine to fine sand (0.05–0.25 mm).

Variations with depth of the average particle size distribution for soils in the Nabou grassland plot and Tulasewa, Korokula and Koromani forest plots are shown in Figure 4.1. The soil in the **Nabou grassland** plot (soil pit) consisted of a brownish-black

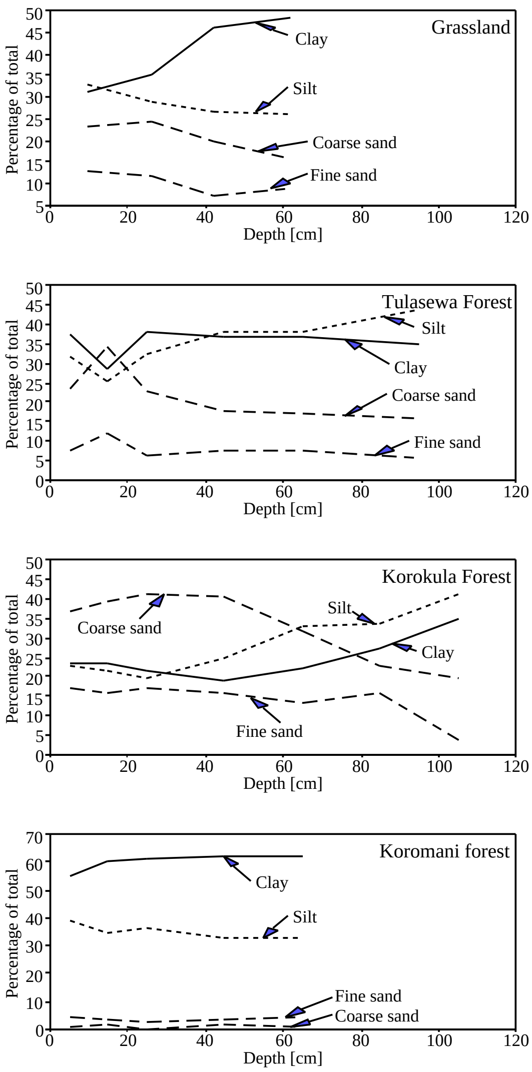


Figure 4.1: *Particle size distribution profiles for the soils in the Nabou grassland plot (soil pit) and those in the Tulasewa, Korokula and Koromani forest plots (spatial averages).*

sandy loam topsoil (0–30 cm), underlain by a reddish-brown clay subsoil (Section 3.1). The particle size distribution of the silt fraction showed a peak at 0.016 mm throughout the profile, whereas that of the sand fraction was observed at 0.5 mm. The silt/clay ratio, which is sometimes used as an index of soil erodibility for water erosion in static laboratory tests (Morgan, 1986), decreased throughout the profile from 1.06 at a depth of 5 cm to 0.81 at 30 cm and 0.54 at 64 cm, suggesting that the erodibility decreased with depth. However, other factors as aggregate stability, infiltration capacity, organic matter content *etc.* are also important factors determining the erodibility, and the index should therefore be interpreted with caution.

Texture profiles for the soil in the **Tulasewa forest** plot were obtained from bulked samples collected at seven sample points. Considerable variation in soil texture was observed within the plot (range clay – clay loam), which may be related to local variations in the depth (0.8–2 m) and composition of the parent rock. The clay loam texture of the upper 10 cm of the soil was similar to that of the subsoil (20–100 cm) but the two layers were separated by a thin layer (±10 cm) of coarser texture (sandy clay loam) as shown in Figure 4.1. The particle size distributions of the sand fraction again showed a peak at 0.5 mm throughout the profile, whereas that of the silt fraction was flat. The silt/clay ratio increased from 0.86 in the topsoil (0–30 cm) to 1.02 in B/C horizon (35–80 cm) and to 1.25 in the lower C-horizon (90–100 cm), indicating that soil erodibility increased with depth.

The texture of the soil in the **Korokula forest** plot was distinctly different from that of the Nabou grassland plot, and those of the Tulasewa and Koromani forest plots, showing large changes with depth. Soil depth at the seven sample points varied between 60 cm and 110 cm. The topsoil (A-, B-horizons, 0–50 cm) was coarser than at the other sites, and consisted of brownish–black sandy clay loam. The texture gradually changed to brown clay loam deeper in the profile (C-horizon) as both the proportions of silt and clay increased. The particle size distributions for the sand fractions showed peaks at 0.4–0.7 mm throughout the profile, whereas that of the silt fraction was flat. In some locations, where the soil was shallow, the C-horizon was thin or absent and the sandy clay loam topsoil was found to directly overlie the bedrock. On other locations the sandy topsoil had been eroded exposing the more massive C-horizon. Somewhat coarser soil was observed at the soil–rock interface due to the presence of strongly weathered rock particles. The silt/clay ratio was 0.93 in the topsoil (0–30 cm) and increased to a maximum of 1.47 at 60–70 cm after which a decrease to 1.17 was observed deeper in the profile. Hence the erodibility was lowest in the topsoil and increased with depth in the C-horizon, followed by a decrease near bedrock.

The soil in the **Koromani forest** plot was a reddish-brown clay and showed very little variation in texture with depth (Figure 4.1). The particle size decreased throughout the silt and sand fractions and no distinct peaks were therefore observed in the distributions of these fractions. The spatial heterogeneity in texture was also low, unlike those observed in the Tulasewa and Korokula forest plots. The silt/clay ratio decreased with depth from 0.69 at 0–10 cm to 0.52 at a 60–70 cm.

Data on the texture of topsoil (0–20 cm) and the subsoil (30–60 cm) in the forested **Oleolega drainage basin** were obtained from soil samples collected at 25 randomly distributed sample points (Figure 15.3). Soil texture showed a large variation within the catchment, ranging from sandy loam to clay. However, two distinct groups could be recognised as shown in Figure 4.2. Relatively coarse textured (sandy loam to clay loam), dull-orange to yellowish-brown soils had developed on the dacite lava flows and tuffs forming the ridges and slopes in the northern part of the catchment,

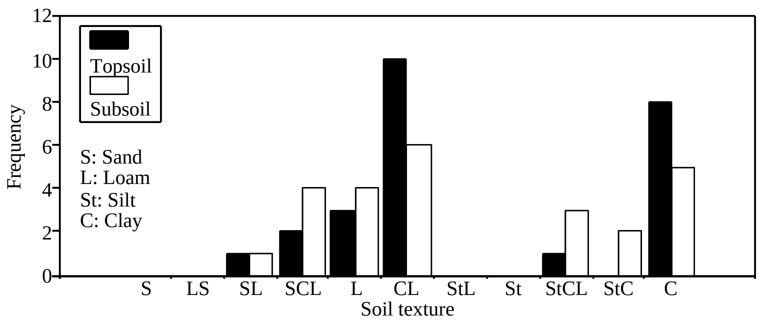


Figure 4.2: *Frequency distribution of texture of top- and subsoils in Oleolega forest based on 25 sample points.*

whereas finer grained (silty clay to clay) dull-orange to bright reddish-brown soils were found overlying andesite and diabase lava flows in the southern part of the catchment (Section 3.5). The differences in texture may reflect differences in weathering of the two rock types. The texture of the topsoil in Oleolega catchment tended to be slightly finer than that of the subsoil, which probably reflected the degree of weathering as subsoil samples were often collected in the zone just above the weathered parent rock and therefore contained weathered rock fragments. The silt/clay ratio averaged 0.96 in the top 20 cm of the soil (range 0.51–1.47) and increased to 1.15 at a depth of 30–60 cm (range 0.45–2.43)

4.3.2 Bulk Density

Figure 4.3 shows the bulk density profiles for the grassland and forest soils. Relatively low bulk densities were observed in the loose, granular A-horizons (0–20 cm) followed by a gradual increase in the more massive B- and C-horizons. In non-eroded yet shallow soils in the Tulasewa and Korokula forest plots the A-horizon was separated from the parent rock by only a thin B/C-horizon resulting in a sharp increase in bulk density near the soil–rock interface (*e.g.* from 1.4 to 2.1 g cm^{-3} in the Korokula forest plot).

Due to the small size of the **Nabou grassland** plot (100 m^2) and the limited number of capacitance probe access tubes (2) it was difficult to speculate on the spatial variation of the bulk density. However, the two profiles were remarkably similar, suggesting that this may have been low.

The spatial variation in topsoil bulk density in the **Tulasewa** and **Korokula forest** plots was considerably larger due to local erosion of the A-horizon, exposing the more massive B- and C-horizons. The spatial variation in bulk density decreased in the subsoil as indicated by the standard deviations in Table 4.2.

In the **Koromani forest** plot bulk density showed little spatial variation. A lithological change (from andesite to dacite?) was observed in the valley at the northern edge of the plot and here the bulk density of the overlying soil was slightly lower than those of the soils on the slope and ridge.

Only one access tube had been installed in the forested **Oleolega catchment**. The variation in bulk density with depth is shown in Figure 15.4 and was similar to those observed in the soils of the Korokula and Koromani forest plots.

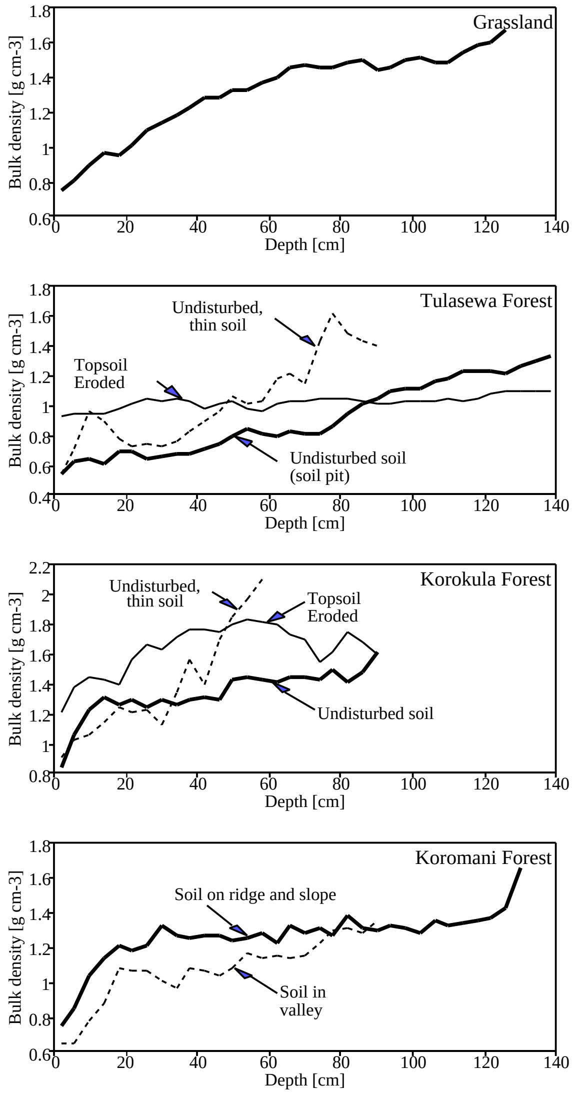


Figure 4.3: *Bulk density profiles for the Nabou grassland plot and for several soil types within the Tulasewa, Korokula and Koromani forest plots.*

Average bulk densities for various depth intervals, corresponding to those at which soil samples had been collected for chemical analyses, were calculated from data collected during installation of the capacitance probe access tubes and from the core sample data. The results are given in Table 4.2 together with significance levels for the differences between site means as calculated with the *Student's t* distribution (Spiegel, 1972). The full set of bulk density data obtained from the soil cores is presented in Appendix 25. Interestingly, the bulk density of the grassland topsoil was not significantly higher than those of the topsoils of the respective forest areas (Table 4.2), although the highest values were observed in Korokula forest. However, bulk densities of the grassland subsoil were significantly higher than observed at corresponding depths in the Tulasewa and Koromani forest plots.

4.3.3 Hydraulic Conductivity

A summary of the data on saturated hydraulic conductivities (K_{sat}) for the topsoils and subsoils under grass and pine forests is presented in Table 4.3, whereas the raw data have been tabulated in Appendix 25. The data were not normally distributed, and median and mode values are therefore included in addition to the means. K_{sat} was generally high in the granular topsoils and decreased sharply in the more massive B- and C-horizons. The spatial variation was high at all sites as indicated by the large range in values. Low hydraulic conductivities were measured in the topsoil of the Tulasewa and Korokula forest plots where the granular A-horizon had been eroded, thus exposing the B/C horizon to the surface, whereas high values were observed in areas where the A-horizon was still present.

The K_{sat} data were not normally distributed and a non-parametric test (Mann-Withney Rank Correlation; Conover, 1980) was used to test whether K_{sat} differed significantly between sites. No significant differences were observed between the grassland plot topsoil and those of the forest plot topsoils. The hydraulic conductivity of the subsoil in the Oleolega catchment was significantly lower ($\alpha = 0.05$) than that in the Koromani forest plot (Table 4.3). No significant differences were observed for the other sites.

4.3.4 Porosity, Moisture Retention and Plant Available Water

Average soil moisture retention curves and unsaturated hydraulic conductivity (K_{unsat} or K_θ) curves were calculated for each site with a computer model (van Genuchten, 1980). The moisture retention data, a description of the model and the resulting model parameters are given in Appendix 25. Separate curves were calculated for topsoils and subsoils. The modelled curves for the Nabou grassland plot are shown in Figure 4.4, whereas those for the Tulasewa, Korokula, Koromani forest plots, and those for the Oleolega catchment are shown in Figures 4.5, 4.6, 4.7 and 4.8, respectively. The average porosity of the soils, represented by the intercept of the retention curve with the X-axis, was high, ranging from 46% for the topsoil of the Nabou grassland plot to 61% for that of the Tulasewa forest plot (Table 4.4). The average porosity of the soils differed significantly between sites with levels of significance higher than 95% ($\alpha <$ 0.05) with the exception of that between Korokula forest and Nabou grassland which differed at the 90% significance level ($\alpha = 0.10$). The porosity of the grassland subsoil decreased significantly to 39%, whereas no significant changes with were observed in the profiles under forest.

Table 4.2: *Average bulk densities and their standard deviations, number of sample points and significance levels for differences between site averages at various depths in the Nabou grassland plot, the Tulasewa, Korokula and Koromani forest plots, and the Oleolega catchment.*

Location	**Depth [cm]:**	0-10	10-20	20-30	30-55	55-80	80-100	100-120	120-150
					Bulk Density [g cm-3]				
NABOU GRASSLAND		0.99	1.03	1.16	1.26	1.40	1.48	1.52	1.63
Standard deviation		*0.18*	*0.11*	*0.09*	*0.01*	*0.05*	*0.00*	*0.00*	*0.00*
Sample points		4	4	4	3	3	2	2	2
TULASEWA FOREST		0.97	0.96	0.98	0.95	1.02	1.10	1.07	1.12
Standard deviation		*0.20*	*0.20*	*0.18*	*0.17*	*0.13*	*0.13*	*0.09*	*0.09*
Sample points		11	8	8	11	10	6	5	4
KOROKULA FOREST		1.16	1.28	1.31	1.51	1.50	1.53		
Standard deviation		*0.14*	*0.08*	*0.14*	*0.18*	*0.16*	*0.15*		
Sample points		12	11	8	8	6	5		
KOROMANI FOREST		0.99	1.15	1.26	1.32	1.29	1.33	1.39	
Standard deviation		*0.16*	*0.14*	*0.11*	*0.11*	*0.06*	*0.05*		
Sample points		10	7	7	12	8	5	1	
OLEOLEGA CATCHMENT									
Forested		1.07	1.14	1.21	1.41+				
Standard deviation		*0.07*		*0.09*					
Number of samples		12		12					
BETWEEN SITE DIFFERENCES IN MEANS									
Grassland <> Tulasewa		ns	ns	>*	>***	>***	>***	>***	>***
Grassland <> Korokula		<**	<***	<*	<**	ns	ns		
Grassland <> Koromani		ns	ns	<*	ns	>**	>***		
Grassland <> Oleolega forested		ns		ns					
Tulasewa <> Korokula		ns	<**	<***	<***	<***	<***		
Tulasewa <> Koromani		ns	<**	<***	<***	<***			
Tulasewa <> Oleolega forested		<*		<***					
Korokula <> Koromani		>***	>**	ns	>***	>***	>**		
Korokula <> Oleolega forested		>**		>**					
Koromani <> Oleolega forested		<*		ns					

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01
+: Assumed value; Underlined values have been obtained by linear interpolation

Table 4.3: *Average, median and mode values, as well as standard deviations (SD) and ranges of the saturated hydraulic conductivity of top- and subsoils in the Nabou grassland plot, the Tulasewa, Korokula, Koromani forest plots, and in the Oleolega catchment.*

Location	**Depth** [cm]	**Average** [m day-1]	**SD**	**Median** [m day-1]	**Mode** [m day-1]	**Minimum** [m day-1]	**Maximum** [m day-1]	**n**
Nabou Grassland	0-30	30	58	6.4	2.8	0.95	161	7
	30-64	0.25	0.18	0.25		0.07	0.43	2
Tulasewa Forest	0-30	18	32	1.5	0.49	0.0003	101	12
	30-75	3.8	8.4	0.13	0.0067	0.0000	29	12
	75-150	0.03	0.04	0.012	0.0027	0.001	0.087	5
Korokula Forest	0-30	30	62	6.3	2.1	0.2	251	16
	30-90	0.09	0.18	0.009	0.001	1E-05	0.41	5
Koromani Forest	0-30	16	23	3.2	2.3	0.01	66	13
	30-64	0.26	0.24	0.23	0.21	0.004	0.75	7
Oleolega Forest	0-35	38	62	6.5	0.6	0.06	225	24

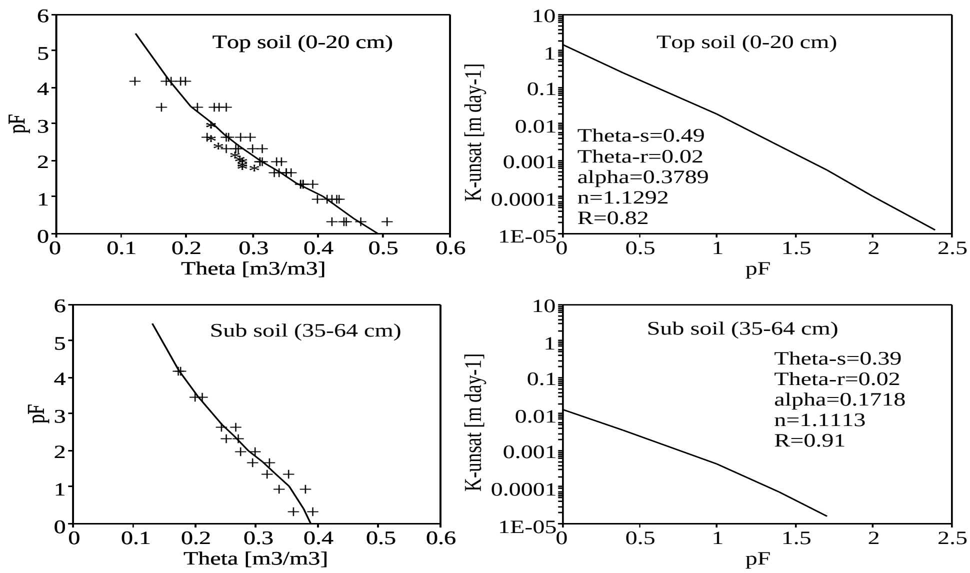


Figure 4.4: *Soil moisture retention curves and modelled unsaturated hydraulic conductivities* versus *pF for the top- (n= 7) and subsoil (n= 2) of the Nabou grassland plot.*

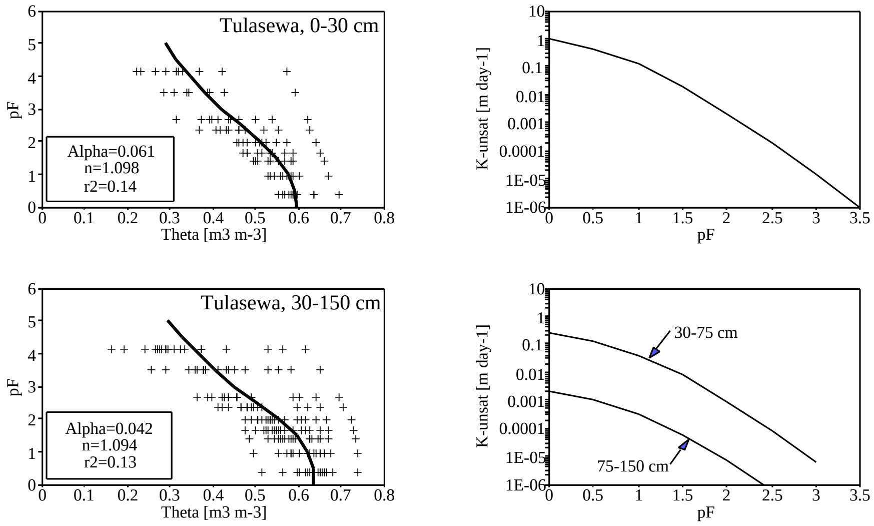


Figure 4.5: *Soil moisture retention curves and modelled unsaturated hydraulic conductivities* versus *pF for the top- (n= 12) and subsoil (n= 17) of the Tulasewa forest plot.*

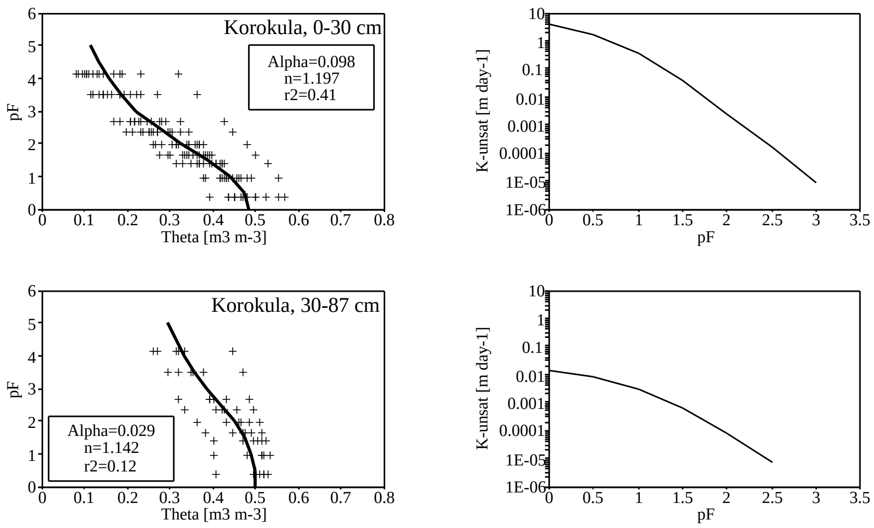


Figure 4.6: *Soil moisture retention curves and modelled unsaturated hydraulic conductivities* versus *pF for the top- (n= 16) and subsoil (n= 5) of the Korokula forest plot.*

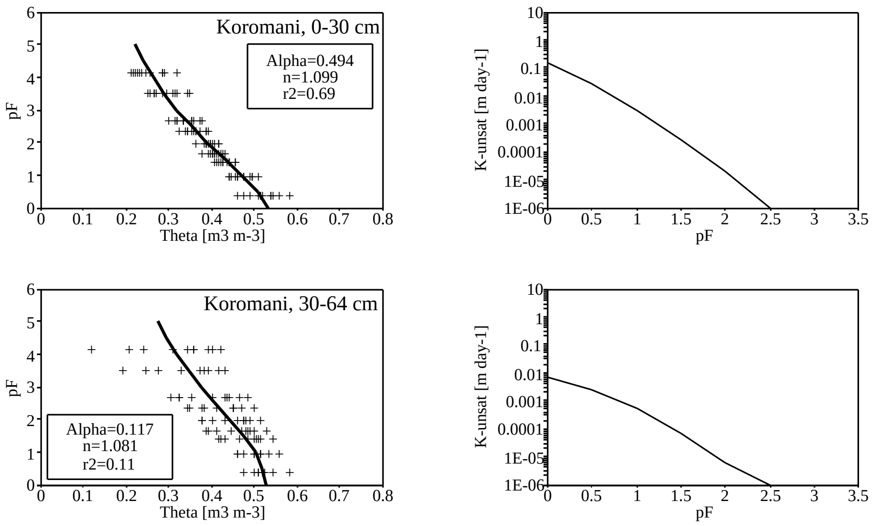


Figure 4.7: *Soil moisture retention curves and modelled unsaturated hydraulic conductivities* versus *pF for the top- (n= 13) and subsoil (n= 7) of the Koromani forest plot.*

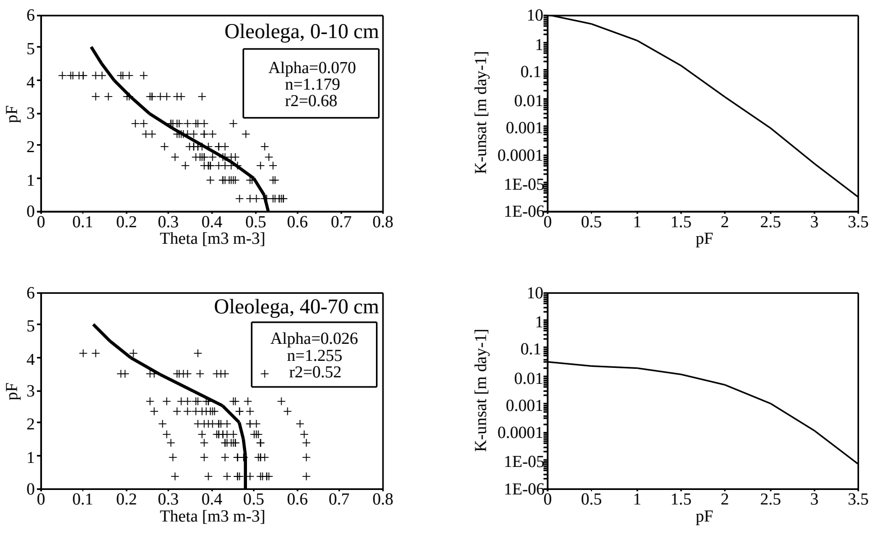


Figure 4.8: *Soil moisture retention curves and modelled unsaturated hydraulic conductivities* versus *pF for the top- (n= 11) and subsoil (n= 11) in the Oleolega catchment.*

Table 4.4: *Porosity, water holding capacity and amount of plant available water for top- and subsoil in the grassland and forest areas. Standard deviations in parentheses.*

Location	Porosity		Water holding capacity		Available water for plants		
	Topsoil %	Subsoil %	Topsoil m3 m-3	Subsoil m3 m-3	0-30 cm mm	30-80 cm mm	0-80 cm mm
Nabou grassland	46 (6)	39 (2)	0.140	0.115	42	58	100
Tulasewa forest	61 (5)	64 (5)	0.184	0.223	55	112	167
Korokula forest	49 (5)	50 (5)	0.195	0.128	59	64	123
Koromani forest	55 (4)	54 (3)	0.142	0.132	43	66	109
Oleolega catchment	58 (5)	51 (7)	0.233	0.226	66	108	174

The water holding capacity of the soils was calculated as the difference in volumetric moisture content (θ) at field capacity (here defined as pF= 2.0) and at permanent wilting point (pF= 4.2). The water holding capacity of the top 30 cm ranged from 0.14 m^3 m^{-3} in Nabou grassland and Koromani forest to 0.22 m^3 m^{-3} in Oleolega catchment (Table 4.4). The plant available water capacities for the upper 30 cm and 80 cm (rooting zone of grass) of the soil were calculated from the water holding capacities of the various soil layers and the results are given in Table 4.4 as well.

The plant available water capacity was lowest in the *Nabou grassland* soil with a total of 100 mm in the upper 80 cm. However, the roots were concentrated in the upper 30 cm of the soil where only 42 mm of water was available. With an estimated grassland evapotranspiration (ET) rate of 2.5–3.5 mm day^{-1} (0.7 times E_0; Blackie, 1979) during the growing season, topsoil moisture would be depleted after a dry period of two to three weeks. Some additional moisture could be extracted from the subsoil but it is unlikely that the grassland vegetation would survive a dry period lasting longer than a month. Dry spells of several weeks are common at the start of the dry season and these may trigger seed production, followed by the dying off of the mission grass (*cf.* Section 10.3).

The plant available water capacity of the soil in the **Tulasewa forest** plot was high and it is therefore unlikely that the forest would experience frequent moisture stress. With an average dry season ET of 4.3 mm day^{-1} (Section 7.7), the upper 80 cm of the soil would only be depleted after 5–6 dry weeks. As the pine roots were observed to extend well beyond this depth additional moisture may be extracted from deeper levels in the soil during dry periods. No signs of water stress were observed during the present study.

Water stress, as indicated by high needle fall (Chapter 12), however, was observed in the **Korokula forest** plot after a dry period of seven weeks in which a total of 23.4 mm of rainfall was recorded. With an estimated dry season ET of 3–4 mm day^{-1} (Chapter 9), soil moisture in the upper 80 cm of the soil would be depleted within five weeks. Although pine roots at Korokula were observed in cracks in the parent rock it is unlikely that large amounts of moisture may be extracted from that zone due to the limited storage capacity of the rock and the value given in Table 4.4 is considered realistic. The undergrowth in Korokula showed signs of wilting on several occasions during the dry season indicating that topsoil moisture had been depleted. However, pine needle litterfall remained low during these periods suggesting that the pines were still able to extract moisture from the subsoil.

The plant available water capacity of the upper 80 cm of the soil in the **Koromani forest** plot was slightly higher than that of the Nabou grassland, but lower than that of Korokula forest. With an average ET of 3.0 mm day^{-1} (Section 7.7) moisture in this layer would be depleted after a dry period of a month. However, no signs of water stress were observed in this forest, even during a seven-week dry period when water stress was observed in the nearby Korokula forest plot, suggesting that moisture was extracted from layers deeper in the profile and the estimate given in Table 4.4 must therefore be considered an underestimate. As in Korokula forest wilting of the undergrowth was occasionally observed at Koromani.

The calculated plant available water capacity of the upper 80 cm of the soil profiles sampled in the Oleolega catchment was high. However, soil depth was often observed to be less than 50 cm on the ridges and shoulders of the catchment, which will limit the amounts of soil water available for the plants in these areas. Additional observations are needed for the proper characterization of the catchment in this respect.

4.3.5 Soil Temperature

The rate of many processes in the soil is a function of temperature, which itself is dependent on factors controlling the impact of solar radiation on the soil (*e.g.* slope, aspect, elevation, plant cover) and soil moisture content (evaporative cooling). Afforestation of grassland is likely to change the soil microclimate due to an increase in the leaf area index of the vegetation, reducing the amount of solar radiation reaching the soil surface. This is generally thought to lead to a more favourable microclimate for the soil fauna which may, in turn, influence decomposition processes in the soil, and therefore its infiltration characteristics and nutrient availability (Lal, 1987).

The impact of afforestation on soil temperature was studied by comparing temperature data collected at a depth of 2 cm in a grassland soil at the top of the Oleolega catchment (240 m a.s.l., Figure 3.4) with those collected at the same depth in the soil of the Tulasewa forest plot (116 m a.s.l.). The grassland plot was situated on a ridgetop where the soil was shallow (depth ± 60 cm) and had a poorly developed structure. The vegetation was typical for the *talasiga* areas consisting of a mixture of ferns and mission grass and had not been burned for at least 15 years. Half-hourly temperature measurements were made during a 63-day period in the wet season of 1991 (February 1 – April 5) and these were compared with data collected during the same period a year earlier in the Tulasewa forest plot. Both sites were flat and topographical aspects, with the exception of the elevation, were similar. The air and soil temperatures at both sites were transformed to those at sealevel to compensate for differences in site elevation, using the temperature lapse rate given in Section 2.4. Because the grassland and forest data had not been collected simultaneously the 9:00 h air temperatures measured at the Nabou weather station for the two periods were compared and the difference was found to be insignificant ($T = 28.2(\pm 1.4)$ °C and $T = 28.4(\pm 1.9)$ °C in 1990 and 1991, respectively).

The air temperatures measured above the grass during the night and the early morning (18:00–10:00 h) were significantly higher ($\alpha = 0.05$) than those measured above forest, but this did not result in a significant difference ($\alpha = 0.05$) between the 24-hour means ($25.4(\pm 2.7)$ °C for forest *versus* $25.8(\pm 2.2)$ °C for grassland) or daytime means. The average diurnal courses of the air and soil temperatures for the grass and forest sites are shown in Figure 4.9. The average soil temperature in grassland ($27.7(\pm 0.9)$ °C) was significantly higher ($\alpha = 0.01$) than that under forest ($25.1(\pm 0.8)$ °C) but the

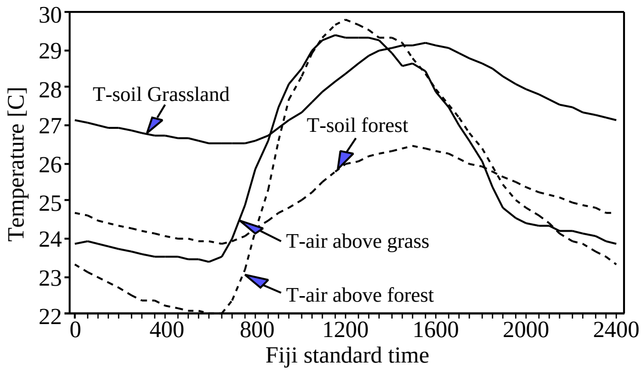


Figure 4.9: *Average diurnal courses of above canopy temperature (T) for grassland (February 1 – April 4, 1991) and 6-year old pine forest (February 1 – April 4, 1990) and corresponding averages of the soil temperature, measured at a depth of 2 cm.*

amplitude was similar at both sites, with differences between mean daily maximum and minimum temperatures reaching 2.5–2.7 °C.

Ghuman and Lal (1985) observed significantly lower soil temperatures (at -5 cm) under natural forest in Nigeria than on cleared land. In contrast to the present findings the amplitude was higher in the latter with differences between the sites of some 2 ° during the night and up to 6 °C during the day. Temperature differences of up to 20–25 °C were observed by Lal and Cummings (1979) in a study comparing soil temperatures (at -1 cm) under forest and cleared land in Nigeria. The low temperature differences observed during the present study indicates that the grass and fern vegetation – litter complex is very effective in shading the soil, preventing high daytime temperatures.

4.3.6 Effects of Afforestation on Soil Physical Characteristics in the Nabou Area

The impact on soil bulk density of the conversion of ungrazed grassland to pine forest was assessed by comparing the bulk density data for the Nabou grassland plot with those observed in the Koromani forest plot, as the two soils were roughly similar in structure, texture and colour. The bulk density of the grassland topsoil was not significantly different from that of the topsoil in Koromani forest which suggested that the effect of afforestation on the topsoil was limited. However, deeper in the soil profile (*e.g.* below the rooting zone of mission grass) the bulk density was significantly higher in the grassland than at corresponding depths in the forest soil. This suggests that improvements in soil structure as a result of afforestation occurred in the subsoil, possibly because of increased root activity, or that the two soils differed from the start, *e.g.* because of geological reasons. This is contrary to the findings of Latham (1983), who worked in 6-year-old *Pinus caribaea* forest and observed that the impact of afforestation on soil properties in Fiji remained confined to the topsoil. Bayliss-Smith (1983) attributed the decrease in bulk density (0.66 g cm^{-3}) and structural instability (0.56) of the top 10 cm of soil under the same 6-year-old pine forest, as compared to adjacent *talasiga* areas (0.77 g cm^{-3} and 0.75 respectively), to afforestation but found no differences in subsoil (50–60 cm) bulk densities (0.98 g cm^{-3} under forest *versus* 1.00 under grass), which were lower that those of the soils presently studied (1.02–1.50 g cm^{-3}). Hence the impact of afforestation on soil bulk density may be variable, possibly depending on initial conditions (*e.g.* soil texture, structure and bulk density, root activity and density of the grass vegetation). Relatively large changes may be expected in soils of poor structure, whereas improvements may be restricted to the subsoil in grassland soils with an already well developed topsoil.

No significant differences were observed between the K_{sat} of the grassland soil and those of the forest soils. However, Bayliss-Smith (1983) observed higher infiltration capacities for the topsoil under 6-year old pine forest (K_{sat}= 78 m day^{-1}) on the island of Lakeba, Fiji, compared to adjacent grassland areas (K_{sat}= 17 m day^{-1}). This again suggests that the impact of afforestation on soil physical conditions depends on initial soil conditions.

The final rates of infiltration, which may be approximated by K_{sat}, of the presently studied (undisturbed) grassland and forest soils were much higher than the prevailing rainfall intensities (Section 6.3) and Hortonian type overland flow (Horton, 1933) was not observed at any of the sites during the study. However, overland flow may have occurred locally during cyclones, although no evidence for this was observed (*e.g.* no litter displacement). Overland flow may also be a regular feature in more severely degraded and eroded grassland soils in the area, especially on ridges and shoulders, where soils are generally poorly developed, the vegetation sparse and rock outcrops common (Rawaqa, 1991). Lateral subsurface stormflow will occur regularly during and shortly after large rainstorms due to the large contrast between K_{sat} of the top- and subsoil (Table 4.3) and this type of flow therefore contributes significantly to total storm runoff (see Chapter 15). Modelled unsaturated hydraulic conductivities in the area for the subsoils were lower than 0.1 mm day^{-1} at soil moisture contents at or drier than field capacity (pF= 2). This indicates that drainage of moisture and leaching of nutrients to deeper soil layers will occur mostly during and shortly after large rainstorms, when percolation rates may exceed the K_{sat} values presented in Table 4.3 due to preferential flow through cracks/macropores.

Although soil porosity estimates were based on a limited number of samples only a comparison of the Nabou grassland data with those for the Koromani forest plot suggested that the deeper root system of the pine trees may have resulted in increases in the (macro)porosity of the subsoil. Higher porosities were also observed by Bayliss-Smith (1983), although not in the subsoil, under 6-year-old pine forest (76%) as compared to adjacent *talasiga* lands (72%).

As indicated earlier, the water holding capacity of the soils was generally sufficient to maintain the water supply to the trees in the study plots during dry periods of several weeks. However, water stress during prolonged dry periods may pose a problem in areas with shallow soils (*e.g.* Korokula forest). Poor growth of pines was also observed on the ridges and shoulders in the Oleolega catchment, where soil depth was less than 50 cm. This may be caused by frequent water stress, although impeded root development in the underlying rock (Van der Weert, 1974) and nutrient deficiencies may also have reduced tree growth. Some support for the water stress explanation comes from the frequent occurrence of *Casuarina* trees, which are known to be drought resistant, on these shallow soils (Mr. T.T. Rawaqa, pers. comm.).

Afforestation resulted in a decrease of the mean daily soil temperature but had no effect on its diurnal course. As the decrease in mean daily soil temperature following afforestation was low (2.5 °C) the effects on soil processes may be relatively small.

Unfortunately no measurements were made for bare soil, which would represent the situation shortly after site preparation and planting of pines. Lal (1987) has shown that temperatures in bare soils may be much higher than those in soils under vegetation due to exposure to solar radiation.

4.4 Soil Chemical Properties

4.4.1 Introduction

The soil is the medium from which nutrients are taken up by the roots for the maintenance and production of biomass. The nutrients are supplied by the stock of available nutrients in the soil. The latter represents a dynamic entity, the magnitude of which is governed by the net balance of nutrient inputs and outputs to and from the soil compartment (*cf.* Chapter 1, Likens *et al.*, 1977). Of particular importance in this respect is the supply of nutrients by weathering of rock and particles of mineral soil (Clayton, 1979; Bruijnzeel and Wiersum, 1985) Weathering aspects and their quantification for the study sites are discussed in more detail in Chapter 14. The effects of afforestation on soil chemical properties may be evaluated using the false time series approach (Hase and Fölster, 1982), provided that the pre-planting chemical properties were similar at the respective sites. In practice, however, this requirement often meets with difficulties (Russell, 1983; Bruijnzeel, 1983a; Buschbacher, 1984). The results of chemical analyses carried out on a large number of soil and rock samples collected at the respective study sites are presented below.

4.4.2 Nutrient Concentrations and Soil Nutrient Status

The bulk chemical composition of distinct soil horizons in the forest plots and those of the parent rock at all sites are presented in Table 4.5. The locations of the rock samples collected in the Oleolega catchment are shown in Figure 15.3. The chemical compositions of rock samples collected near the Nabou grassland plot, the Tulasewa forest (rock sample 1), Korokula forest plots, and in the northern part of the Oleolega catchment were all similar to that of a typical dacite in SW Viti Levu as given by Hathway and Colley (1989). This supported the optical classification of the rocks, as given in Chapter 3. Dacites are high in Si, Al and Na and low in Fe, reflecting the high quartz (SiO_2) and albite ($NaAlSi_3O_8$) contents. The composition of the second sample collected in Tulasewa forest, and those of rocks collected in Koromani forest and in the southern part of the Oleolega catchment, were all typical for andesites or basalts with lower Si and higher Al, Fe and Ca concentrations. Volcanic rocks in SW Viti Levu are generally low in K and P, with the highest values observed in basalts and Kalaka dacites respectively (Hathway and Colley, 1989).

The soils of Tulasewa and Koromani forests contained similar concentrations of Al and Fe whereas values for these elements were lower in the soil at Korokula forest. Concentrations of Al and Fe were relatively low in the topsoil (0–30 cm) and increased in the subsoil reaching a maximum in the B-horizon at a depth between 40 and 70 cm, followed by a gradual decrease in the C-horizon and the saprolite. Although concentrations of Ca, Mg and K were highest in the rock substrate at Koromani forest, those in the soil were distinctly lower than those observed in the soils of Tulasewa and Korokula forests. This, in combination with the high Al and Fe concentrations, suggested that the soil in Koromani forest represents an advanced stage of weathering

Table 4.5: *Bulk chemical composition of the parent rock in the study areas and that of distinct soil horizons in the Tulasewa, Korokula and Koromani forest plots. Analyses of typical dacitic and basaltic rocks in SW Viti Levu (Hathway and Colley, 1989) are included for comparison.*

Depth [cm]	SiO2 %	TiO2 %	Al2O3 %	Fe2O3 %	MnO %	MgO %	CaO %	Na2O %	K2O %	P ^ ppm	Cr2O3 %	V2O5 %	Sum %
Nabou grassland													
Rock+	65.80	0.41	15.00	4.58	0.10	2.33	5.02	2.59	2.03	188.0	0.003	0.018	97.9
Tulasewa Forest (soil pit)													
0-8	60.61	1.24	20.55	12.86	0.14	1.50	0.35	0.59	0.46	6.8			98.3
19-26	54.17	1.34	27.26	14.48	0.07	1.85	0.27	0.33	0.35	7.5			100.1
35-40	48.13	1.31	32.83	15.80	0.06	2.29	0.21	0.07	0.22	7.3			100.9
50-63	48.86	1.32	33.83	13.16	0.19	2.11	0.15	0.07	0.20	5.8			99.9
75-80	48.12	1.33	32.82	14.01	0.35	2.11	0.15	0.07	0.22	0.4			99.2
115-130	53.78	1.16	27.68	11.78	0.10	2.00	0.17	0.22	0.41	3.8			97.3
Rock@	46.10	1.65	23.02	12.66	0.39	2.37	8.51	3.35	0.32	0.2			98.4
Rock+	71.90	0.50	14.80	2.45	0.07	1.95	0.24	6.33	0.23	246.7	0.005	0.003	98.6
Korokula Forest (soil pit)													
0-10	71.66	0.88	8.04	2.96	0.04	0.35	0.31	0.64	0.26	22.1			85.1
20-30	77.26	0.84	8.55	4.13	0.09	0.29	0.20	0.46	0.37	20.1			92.2
40-50	56.16	1.01	24.88	11.86	0.10	1.41	0.32	2.77	0.36	6.5			98.9
60-70	48.33	1.21	27.51	14.90	0.50	3.65	1.54	2.86	0.20	7.3			100.7
80-90	48.93	1.27	25.77	14.13	0.27	5.38	1.82	3.14	0.39	10.4			101.1
Rock@	64.98	0.62	16.28	5.00	0.11	2.25	1.68	5.01	0.12	0.9			96.1
Rock+	67.60	0.66	14.40	4.99	0.09	2.68	2.10	5.39	0.09	406.1	0.004	0.008	98.2
Koromani Forest (soil pit)													
0-10	55.73	2.07	26.89	14.92	0.10	0.47	0.19	0.12	0.15	2.4			100.6
14-20	56.70	1.92	27.75	14.94	0.08	0.42	0.13	0.10	0.15	5.3			102.2
43-53	44.52	1.26	36.00	19.92	0.06	0.31	0.03	0.06	0.16	0.9			102.3
73-93	48.03	1.55	34.23	17.24	0.06	0.38	0.03	0.07	0.13	1.4			101.7
97-105	52.48	1.44	32.12	13.45	0.05	0.35	0.04	0.06	0.10	1.4			100.1
152-162	53.90	1.57	31.32	12.82	0.04	0.35	0.03	0.06	0.08	1.4			100.2
Rock@	48.44	1.56	18.52	13.49	0.21	4.62	4.10	5.43	1.41	0.2			97.8
Rock+	51.60	0.91	17.50	10.92	0.21	6.43	6.34	4.50	0.49	246.6	0.009	0.063	99.0
Oleolega Catchment													
Rock1+*	52.30	1.17	15.90	15.76	0.29	6.64	4.21	4.70	0.10	320.9	0.007	0.058	101.2
Rock2+*	60.40	0.56	16.40	7.58	0.76	3.06	5.16	3.21	0.24	272.9	0.006	0.020	97.5
Rock3+*	76.70	0.27	12.10	2.39	0.10	1.59	0.30	4.46	0.63	91.7	0.003	0.001	98.6
Typical dacite (Koroviko point)													
	70.3	0.4	14.6	2.0	0.8	0.2	0.4	8.0	0.3	1637			97.7
Typical Basalt (Sigatoka Valley)													
	48.5	0.6	19.7	9.0	0.2	4.2	8.6	3.4	2.3	437			97.5

^: Available P (P-Bray II extraction) for soil samples, total P for rock samples

+: Fresh rock, samples analysed on mass spectrometer. @: Rotten rock, P-Bray II analysis

* Rock1 collected in stream channel at outlet, rock2 and rock3 collected in stream channel at sample point 14

Table 4.6: *Bulk element content (t ha^{-1}) of the top 100 cm of the soils in Tulasewa, Korokula and Koromani forests.*

Site	Depth	Na	K	Ca	Mg	Si	Ti	Al	Fe	Mn
Tulasewa Forest	0-100	16.3	27.8	19.1	156.3	3035.7	100.0	2072.3	1257.5	17.6
Korokula Forest	0-100	244.5	36.9	96.9	221.5	3828.3	92.5	1623.6	1094.8	25.7
Koromani Forest	0-100	6.4	14.3	5.1	27.8	2923.9	115.5	2187.6	1476.1	6.5

(Mohr *et al.*, 1972). The soil in Tulasewa was somewhat richer in alkali and alkali earth elements (*e.g.* Mg) and represented an intermediate stage of weathering, which is supported by the presence of the original rock structure in the rotten rock and deeper parts of the subsoil. The shallow soil in Korokula forest was in an early stage of weathering with high concentrations of Ca, Mg, Na, K, Mn and Si, reflecting the presence of weatherable rock fragments, and relatively low Fe and Al concentrations. Concentrations of 'Available' P (P-Bray II) decreased with depth in the profiles and were low to very low in all soils (Table 4.5).

Estimates of total element contents of the 0–100 cm soil layer in the forest plots are given in Table 4.6. Differences between the sites were large and reflected the weathering stage of the substrate as discussed earlier. Weathering of minerals in the soil and parent rock of Korokula forest, and to a lesser extent in those of Tulasewa and Koromani forests, could provide nutrients for uptake by the vegetation and the nutrient cycles for these forest must be considered open (Baillie, 1989).

Khanna and Ulrich (1984) grouped soils in five classes based on the stability of soil minerals and oxides and the possible buffering reactions involving protons (H^+) in freely drained soils. The respective buffering ranges were:

- Calcium carbonate buffer range ($pH_{H2O} > 6.2$)
- Silicate buffer range ($5.0 < pH_{H2O} < 6.2$)
- Cation exchange buffer range ($4.2 < pH_{H2O} < 5.0$)
- Aluminium buffer range ($3.8 < pH_{H2O} < 4.2$)
- Iron buffer range ($2.4 < pH_{H2O} < 3.8$)

The pH_{H2O} of soils in the Nabou forest estate ranged from 4.2 to 6.3 in the topsoil and from 3.5 to 4.8 in the subsoil (Leslie *et al.*, 1985), encompassing the silicate, cation exchange, aluminium and iron buffer ranges of Khanna and Ulrich (1984).

In soils with pH_{H2O} values in the silicate buffer range the soil is buffered by the weathering of silicates, releasing alkali (*e.g.* Na, K) and alkali earth (*e.g.* Ca, Mg) cations which occupy the exchange sites of clay minerals formed in the weathering process. The H^+ ions consumed in the process combine with Si to form silicic acid (H_4SiO_4, which eventually breaks down to H_2O and SiO_2) and leaching of Si is therefore not accompanied by large losses of other cations. Concentrations of HCO_3^- and NO_3^- are low in these soils. Therefore leaching losses from these soils can considered to be relatively low. Gradients of chemical soil properties with depth are relatively small and the C/N ratio in the root zone is low. The associated high turnover rate and the high amount of nutrients in the rooting zone provide a well balanced and adequate supply of nutrients to plants (Khanna and Ulrich, 1984).

In soils where pH_{H2O} values are within the cation exchange buffer range the Al in the lattices of clay minerals is substituted by H^+ ions. The released Al^{3+} ions form polymeric hydroxy cations with a charge of +0.5 per Al atom and accumulate in the interlayers of swelling clays, replacing alkali and alkali earth ions which are consequently leached. Phosphate combines with Al and Fe to form complexes of lower solubility than those in the silicate buffer range (Sanchez, 1976). Therefore nutrient deficiencies may occur in these soils (Khanna and Ulrich, 1984). Gradients in chemical properties with depth are usually larger than those of soils in the silicate buffer range.

At soil pH_{H2O} values below 4.2 $Al(OH)_3$ becomes soluble and alkali and alkali earth cations are exchanged against Al^{3+} ions and leached. Levels of exchangeable Al are therefore high and those of exchangeable Ca and Mg are reduced to less than 5–10% of the cation exchange capacity (CEC). The high Al concentration in the soil solution is sometimes claimed to be toxic for tree species (Sanchez, 1976; Khanna and Ulrich, 1984). These soils usually contain low quantities of exchangeable K, Ca and Mg, organic matter, N and soluble P whereas trace elements (*e.g.* Mn, Zn) become soluble as well and may therefore be leached or reach toxic levels in the soil solution (*e.g.* Mn). As such, poor growth may be expected on soils in this buffer range (Khanna and Ulrich, 1984). Because pH_{H2O} values below 3.8 were seldomly encountered in the presently studied areas the iron buffer range will not be discussed here. Suffice to say that soils in this buffer range contain more toxins and greater nutrient deficiencies than those in the aluminium buffer range (Khanna and Ulrich, 1984).

The pH_{KCl} is usually lower than the pH_{H2O} due to a net negative charge of soil particles and indicates the buffer range which would be attained as a result of high inputs of protons or cations (*e.g.* after fertilization).

The soil pH_{H2O}, pH_{KCl}, %N, %C and LOI were determined in the grassland and forest soils, whereas concentrations of exchangeable cations, NO_3 and 'available' P (as determined with the Ca-Lactate method and given as PO_4) were determined in the forest soils only since these are likely to show a seasonal fluctuation in the grassland soil, corresponding with that of the growth pattern of the vegetation (*cf.* Section 10.3). Furthermore, Leslie *et al.* (1985) has already presented data on the exchangeable cations and 'available' P (Olsen's extraction method) in four grassland soils in the Nabou area. The analytical data is presented in Appendix 26, whereas weighted averages of the respective parameters are given in Table 4.7. Significance levels for any differences in means between the sites are presented in Table 4.8. Standard deviations were calculated both from the individual sample data and from a combination of the latter and bulked samples. Standard deviations for the latter were higher and these were therefore used to calculate the significance levels. This also enabled the calculation of significance levels for the differences in subsoil parameters for which only bulk samples were analysed. However, actual site heterogeneity may well have been underestimated and differences in means with significance levels lower than 95% (α= 0.05) should be considered insignificant. No comparisons could be made between the grassland and forest sites as only one sample was collected from each distinct horizon in the former (see also Section 4.4.3, however).

The pH_{H2O} of the soil of the **Nabou grassland** plot was within the silicate buffer range and showed little variation with depth. The difference between the pH_{H2O} and the pH_{KCl} was small and positive (0.3–0.5) suggesting that cations other than H^+ occupied the exchange sites, which would result in a high base saturation. The pH_{H2O}, %N and LOI fell within the range of those observed in the forest soils. However, the pH_{KCl} was distinctly higher and the %C and the C/N ratio were lower than those of

Table 4.7: *Weighted average concentrations of soil chemical properties at various depths in the soils of the Nabou grassland plot, the Tulasewa, Korokula, Koromani forest plots, and the Oleolega catchment (n represents the number of sample points; 'Available' P (Ca-Lactate method) given as PO_4).*

Site	**Depth**	**n**	**pH**	**pH***	**N**	**C**	**C/N**	**LOI**	**Na**	**K**	**Ca**	**Mg**	**NH4**	**NO3**	**PO4**
	[cm]				[%]	[%]		[%]			[meq 100 g-1 soil]				
Nabou Grassland	8-12	1	5.20	4.70	0.169	2.09	12.4	8.9							
	24-28	1	5.32	4.89	0.103	0.97	9.4	7.4							
	40-44	1	5.31	4.90	0.057	0.31	5.4	6.7							
	60-64	1	5.22	4.91	0.071	0.43	6.1	5.9							
Tulasewa Forest	0-10	13	5.05	3.97	0.171	2.55	15.0	9.9	0.158	0.133	2.63	6.93	0.057	0.006	0.005
	10-20	12	5.14	3.97	0.119	1.52	12.7	9.7	0.141	0.080	2.30	6.98	0.032	0.007	0.004
	20-30	13	5.06	3.81	0.086	1.15	13.3	8.6	0.185	0.065	2.22	6.92	0.018	0.011	0.005
	40-50	13	5.16	3.85	0.039	0.48	12.2	7.2	0.218	0.068	1.27	7.05	0.008	0.007	0.002
	60-70	13	5.33	3.90	0.025	0.25	10.3	6.9	0.278	0.082	1.07	8.39	0.004	0.005	0.002
	90-100	8	5.42	4.39	0.017	0.14	8.3	6.6	0.335	0.089	1.40	9.58	0.006	0.005	0.002
	115-130	1	5.58	4.13		0.01			0.360	0.110	2.06	11.96			
Korokula Forest	0-10	13	5.44	4.36	0.142	2.20	15.4	6.6	0.212	0.061	2.31	3.51	0.056	0.028	0.010
	10-20	12	5.51	4.32	0.118	1.72	14.6	6.2	0.225	0.042	2.25	3.89	0.040	0.021	0.004
	20-30	8	5.55	4.24	0.079	1.25	15.9	5.0	0.196	0.020	1.39	3.14	0.022	0.004	0.005
	40-50	13	5.57	4.16	0.041	0.57	13.9	4.7	0.231	0.032	1.04	5.62	0.004	0.007	0.003
	60-70	13	5.79	4.21	0.022	0.31	13.9	4.8	0.342	0.030	0.56	7.99	0.001	0.007	0.002
	80-90	5	6.07	4.32	0.023	0.22	9.6	5.3	0.339	0.025	0.29	8.63	0.001	0.005	0.003
	100-110	1	5.92	4.68	0.042	0.59	14.0	7.0	0.593	0.011	0.32	10.03	0.001	0.003	0.002
Koromani Forest	0-10	13	4.73	4.02	0.188	3.47	18.5	14.0	0.193	0.053	2.33	2.19	0.061	0.018	0.012
	10-20	13	4.83	3.95	0.111	1.87	16.8	11.7	0.110	0.023	1.16	1.28	0.027	0.010	0.004
	20-30	12	4.83	3.87	0.080	1.37	17.1	9.6	0.071	0.015	0.77	0.94	0.014	0.008	0.003
	40-50	13	4.79	3.82	0.052	0.65	12.5	9.4	0.078	0.013	0.23	0.43	0.008	0.008	0.003
	60-70	13	4.60	3.84	0.041	0.50	12.3	9.5	0.076	0.014	0.15	0.33	0.006	0.008	0.002
	90-100	1	4.68	4.05		0.19			0.290	0.020	0.60	0.63			
	140-150	1	4.46	4.01		0.11			0.310	0.020	0.56	0.54			
Oleolega Forest	0-10	25	4.60	3.97	0.136	2.22	16.3	8.3	0.170	0.114	1.28	1.93	0.170	0.129	0.013
	10-20	25	4.56	3.87	0.084	1.25	14.8	7.1	0.118	0.081	0.75	1.67	0.133	0.068	0.004
	30-60	25	4.72	3.83	0.033	0.37	11.3	6.2	0.127	0.062	0.29	2.06	0.070	0.025	0.001

pH*: pH of soil in KCl solution

Table 4.8: *Significance levels for differences in mean values, calculated using the* Student's t *distribution, of soil chemical properties in the Tulasewa, Korokula and Koromani forest plots and the forested Oleolega catchment.*

Location	Depth	n	pH	pH*	%N	%C	C/N	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
Significance levels of differences between means															
Depth interval 0-10 cm															
Tulasewa <> Korokula			<***	<***	>*	ns	ns	>***	<**	>***	>*	>***	ns	<***	<***
Tulasewa <> Koromani			>***	ns	ns	<***	<***	<***	<*	>***	>*	>***	ns	<**	<***
Tulasewa <> Oleolega			>***	ns	ns	ns	<**	>**	ns	ns	>***	>***	<***	<**	ns
Korokula <> Koromani			>***	>***	<***	<***	<***	<***	ns	ns	ns	>***	ns	ns	ns
Korokula <> Oleolega			>***	>***	ns	ns	<**	<***	<**	<***	>***	>***	<***	<**	ns
Koromani <> Oleolega			ns	ns	>**	>***	ns	>***	ns	<***	>***	ns	<***	<**	ns
Depth interval 10-20 cm															
Tulasewa <> Korokula			<***	<***	ns	ns	<**	>***	<***	>***	ns	>***	ns	<***	ns
Tulasewa <> Koromani			>***	ns	ns	<*	<***	<***	>**	>***	>***	>***	ns	ns	ns
Tulasewa <> Oleolega			>***	ns	>***	<*	<**	>***	ns	ns	>***	>***	<***	<***	ns
Korokula <> Koromani			>***	>***	ns	ns	<***	<***	>***	>***	>***	>***	>**	>**	ns
Korokula <> Oleolega			>***	>***	>**	>***	ns	<*	>***	<***	>***	>***	<***	<**	ns
Koromani <> Oleolega			>**	ns	>**	>***	ns	>***	ns	<***	>**	ns	<***	<**	ns
Depth interval 40-50 cm															
Tulasewa <> Korokula			<***	<***	ns	ns	<***	>***	ns	>***	>*	>**	>***	ns	ns
Tulasewa <> Koromani			>***	ns	<**	<***	ns	<***	>***	>***	>***	>***	ns	ns	>**
Tulasewa <> Oleolega			>***	ns	ns	ns	ns	>*	>***	ns	>***	>***	<***	<***	>**
Korokula <> Koromani			>***	>***	<**	ns	>*	<***	>***	>***	>***	>***	<***	ns	ns
Korokula <> Oleolega			>***	>***	>*	>**	>*	<**	>***	<**	>***	>***	<***	<***	>***
Koromani <> Oleolega			ns	ns	>***	>***	ns	>***	<**	<***	ns	<**	<***	<**	>***

pH*: pH of soil in KCl solution
ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

Table 4.9: *Sums of cations (SUM, meq 100 g^{-1} soil), cation exchange capacity (CEC, meq 100 g^{-1} soil), and base saturation (BS, %) at various depths in the soil pits at the Tulasewa, Korokula and Koromani forest plots.*

	Tulasewa				**Korokula**				**Koromani**		
Depth	**SUM**	**CEC**	**BS**	**Depth**	**SUM**	**CEC**	**BS**	**Depth**	**SUM**	**CEC**	**BS**
0-8	20.0	23.3	86	0-10	6.3			0-10	6.9	8.6	81
19-26	22.0	23.4	94	18-35	5.2	5.4	97	14-20	5.6	7.7	83
35-40	29.2	31.4	93	40-50	20.9	20.8	101	43-53	3.5	5.8	62
50-63	28.1	30.7	92	60-70	36.2	35.6	102	73-93	3.6	5.1	71
75-80	27.7	30.1	92	80-90	38.8	36.3	107	97-105	3.1	4.9	67
115-130	30.8	31.4	98					152-162	2.9	5.4	56

the forest soils.

The pH_{H2O} of the topsoil in the **Tulasewa forest** plot was just above the lower limit of the silicate buffer range and increased in the subsoil to values well within the silicate buffer range. The pH_{KCl} showed a minimum in the B-horizon and was 1.0–1.4 units lower than the pH_{H2O} indicating that protons occupied a significant proportion of the exchange sites. The increase in soil pH_{H2O} with depth was accompanied by increases in exchangeable Mg and to a lesser extent Na, which were larger than corresponding decreases in exchangeable K, Ca, NH_4 and 'available' P. Exchangeable NO_3 was low throughout the profile. Exchangeable Ca and Mg were significantly higher than in any of the other forest soils. The CEC was determined for samples collected in the soil pit and increased from 23 meq 100 g^{-1} soil in the topsoil to 31 meq 100 g^{-1} soil in the subsoil as shown in Table 4.9. The base saturation was high throughout the profile and increased from about 90% in the topsoil to 98% below a depth of 100 cm (Table 4.9).

The soil in the **Korokula forest** plot was well within the silicate buffer range with a pH_{H2O} increasing from 5.1 in the topsoil to 6.0 in the subsoil. Both pH_{H2O} and pH_{KCL} were significantly higher than in any of the other forest plots. A minimum in the pH_{KCl} value was again observed in the B-horizon. The difference between the pH_{H2O} and the pH_{KCl} in the topsoil was similar to that observed in Tulasewa forest but increased to about 1.7 in the soil just above the bedrock. Exchangeable Mg and Na increased with depth with corresponding decreases in exchangeable K, Ca, NH_4 and 'available' P. The CEC of samples collected in the soil pit was low in the topsoil at about 6 meq 100 g^{-1} soil in the topsoil and increased sharply in the subsoil to 36 meq 100 g^{-1} soil. Base saturation was high, however, ranging from 85% in the topsoil to 100% in the subsoil (Table 4.9).

The soil in the **Koromani forest** plot was in the cation exchange buffer range with a pH_{H2O} decreasing from about 4.8 in the topsoil to a minimum of 4.5 in the subsoil. The pH_{KCl} showed a minimum in the B-horizon and was less than one unit lower than the pH_{H2O} throughout the soil profile. The carbon content and LOI were significantly higher than those in the other forest plots but amounts of exchangeable cations were low, which is normal for soils in this buffer range (Khanna and Ulrich, 1984). The CEC of samples collected in the soil pit was low and decreased gradually from about 8 meq 100 g^{-1} soil in the topsoil to about 5 meq 100 g^{-1} soil in the subsoil. Base saturation was lower than at the other forest sites and decreased from 80% in the topsoil to 50–70% in the subsoil (Table 4.9).

The pH_{H2O} showed a large spatial variation within the **Oleolega catchment** with minimum values of 3.97 and 4.20 and maximum values of 5.34 and 5.66 in top- and subsoil respectively (Appendix 26). The average pH_{KCl} was less than a unit lower than the pH ranging from 3.14 to 4.65 and from 3.36 to 4.87 in top- and subsoil respectively. Exchangeable cations were low with the highest amounts observed for Mg. Most of the soils were in the cation exchange buffer range which explained the low averages of exchangeable cations as compared to those observed in the soils of Korokula and Tulasewa forests. However, exchangeable NH_4 and NO_3 were significantly higher than those in the forest plot soils. The increase in spatial variation with depth in the profile (Appendix 26) may reflect the proximity of the weathering zone just above the parent rock.

The spatial variation of soil chemical characteristics was lowest in the Koromani forest plot and highest in the Oleolega catchment where samples were taken from various soil types. The degree of variation differed for respective soil properties. The lowest variations were observed for pH_{H2O}, pH_{KCl} and LOI, of which the standard

Table 4.10: *Amounts of total C and N (kg ha^{-1}) in grassland and forest soils and available nutrients (kg ha^{-1}) in the forest soils.*

Location	Depth	Na	K	Ca	Mg	P+	P*	NH4-N	NO3-N	N-Tot	C-Tot
Nabou grassland	0-60									6901	66245
Tulasewa Forest	0-60	321	220	2462	6091	2.4	50	19	7	5329	71178
Korokula Forest	0-60	441	115	2351	4907	3.6	110	23	13	5884	87458
Koromani Forest	0-60	163	58	1096	783	3.2	16	19	10	6123	97659
Oleolega Forest	0-60	230	220	816	1837	2.7		105	53	4513	63563
Nabou grassland	0-100									11048	91357
Tulasewa Forest	0-100	727	411	3895	12377	3.5	78	23	11	6528	82517
Korokula Forest	0-100	915	179	2866	11029	5.0	164	24	18	7242	103368
Koromani Forest	0-100	386	93	1495	1091	3.8	24	22	13	7184	115716

P+: Ca-Lactate extraction method; P*: Bray II extraction method, soil pits only

deviations usually were less than 10% of the respective means. Larger variations were observed for %N, %C and exchangeble Ca and Mg of which the standard deviations were generally between 10% and 30%, whereas those for exchangeable Na, K and NH_4 were even higher with standard deviations of 25% to 40%. The spatial variation was highest for 'available' P and exchangeable NO_3 whose standard deviations were as large as the corresponding averages (Appendix 26).

Significant differences between the sites were observed for most chemical properties, as well as for bulk densities which resulted in large differences in soil nutrient contents (Table 4.10). Total N and C contents and available nutrient contents for the top 60 and 100 cm of the soils in the Tulasewa, Korokula and Koromani forest plots, and in the Oleolega catchment (0–60 cm only) are presented in Table 4.10 together with the total N and C content of the grassland soil. High amounts of N were observed in the Nabou grassland soil and to a lesser extent in the Koromani forest plot, whereas low amounts were observed for the Oleolega catchment, despite high values for available N in the latter area (NH_4 and NO_3). Contents of Na, K, Ca, Mg and P-Bray II were lowest in Koromani forest, in line with earlier statements for this site.

4.4.3 Effects of Afforestation on Soil Chemical Properties in the Nabou Area

As indicated earlier, the false time series approach to evaluate the impacts of afforestation on soil chemical properties is based on the assumption that pre-planting soil conditions were similar at all sites. The data presented in the previous sections show that this assumption was not justified for the sites in Nabou, due to slight differences in parent rock and above all due to differences in the weathering stages of the respective soils. As such, the effects of afforestation could not be separated from initial site differences. In addition, only a single soil profile was analysed for the Nabou grassland site and significance levels for differences between soil chemical characteristics of the grassland and the forest sites (*e.g.* Koromani forest) could not be calculated.

However, some general conclusions may be drawn from the available data. Soil pH_{H2O} seemed to decrease with age of the forest (with the exception of Korokula forest; Table 4.7), which suggests that protons occupied an increasingly larger portion of the exchange complex in time. This suggests that at least part of the nutrients accumulated in the forest biomass were extracted from the exchange complex, rather than being supplied by weathering or atmospheric inputs. The low base saturation in the Koromani forest plot soil compared to Tulasewa and Korokula forest plot soils could not be used as an indicator for nutrient depletion since base saturation values measured in four grassland soils in the Nabou area by Leslie *et al.* (1985) ranged from 54 to 102% in the topsoil and from 28 to 84% in the subsoil. Some depletion of the soil nutrient reserves may have occurred at the Koromani site after the establishment of the forest, but no such indications were found at the Korokula and Tulasewa forest plots (see Chapter 14 for a more detailed discussion).

The carbon content of the soil seemed to increase with forest age, which resulted in an increase of the C/N ratio as nitrogen content remained fairly constant.

Concentrations of 'available' P were extremely low, particularly when determined with the Ca-lactate method (Table 4.7). Higher P values were obtained with the more agressive P-Bray II method for the samples collected from the soil pits, and the latter method may provide a more realistic representation of the amounts of P in the Fiji soils as they are available over longer periods of time (Dr. V.J.G. Houba, pers. comm.).

The quantification of soil nutrient contents for each of the sites revealed that the nutrient status in Koromani forest was low compared to the other sites. The soil in Tulasewa forest had the highest nutrient contents, which may partly explain the high growth rates observed for that site (Section 11.3.4). The decrease in Ca and Mg contents in topsoil with increasing forest age must be attributed to differences between sites, rather than to uptake by the trees in view of the relatively large quantities of these nutrients in the soil. The available amounts of nutrients may be higher than those presented in Table 4.10 as the pine roots were observed to extend into the weathering zone and bedrock below 100 cm. Nutrients released by weathering may therefore be used by the vegetation, in addition to those present on the soil exchange complex (*cf.* Chapter 14).

Few studies have presented data on the available nutrients in the soil in *Pinus caribaea* plantation forests (Table 4.11) and, strictly speaking, the estimates presented in Table 4.11 cannot be compared to those presently found due to differences in the extraction methods. However, it seems that the soils in the study sites in Fiji are relatively nutrient-rich compared to those of the cited *Pinus caribaea* plantation forests elsewhere, despite similarities between the overall geological settings of SW Viti Levu (Section 2.2) and Puerto Rico (soil on diabase intrusion). Chemical analyses of soils under *Pinus caribaea* forest have been presented by Stark (1970) for Spodosols in Surinam, Chijioke (1980) for Ultisols in Brazil, and Kadeba (1991) for a Cambisol in Nigeria but soil nutrient contents could not be calculated due to the absence of bulk density data.

As the soil fertility is a key factor in the determination of whether plantation forestry can be sustainable, additional regional data needs to be collected in this respect to cover the soil variation. The response of soil fertility to plantation forestry could properly be evaluated by periodic sampling (*e.g.* once every five years) preferably in permanent sample plots so that the fertility can be related to tree growth, and deficiencies can be detected early. The sampling should include both samples for chemical analyses and for bulk density determinations to enable the calculation of the soil nutrient reserves. To evaluate the fertility of different soils, and the impact of various tree species on the fertility, the sampling programme should preferably be carried out in a pan-tropical network of plantation forests. The lack of standard extraction techniques for the determination of exchangeable cations and particularly

Table 4.11: *Summary of amounts of total N and available nutrients (kg ha^{-1}) in Pinus caribaea forest soils.*

Location	Soil type/texture	Dept [cm]	Forest age	N	P	K	Ca	Mg	Reference
Tulasewa	Udic Haplustoll	0-60	7	26	50	220	2462	6091	Present study
Korokula	Udic Haplustoll	0-60	12	36	110	115	2351	4907	
Koromani	Typic Eutrustox	0-60	16	29	16	58	1096	783	
Oleolega	Clay-Sandy loam	0-60	16	158		220	816	1837	
Nabou+	Clay-sandy loam	0-60	0-8	5737*	23	516	6498	6778	Leslie et al. 1985
Brazil	Ultisol/sandy	0-10	9.5	4487*	28	49	109	41	Russell 1983
Trinidad	Fine sandy clay	0-7.6	4	944*	4	28	151	42	Cornforth 1970
	Sandy loam	0-7.6	4	799*	3				
	Gravelly/Fine sand	0-7.6	6	978*	4	19	152	27	
	Fine sand	0-7.6	7	1502*	4	16	382	78	
Puerto Rico	Clay	0-10	4.5	8929*	1710*	31480*	2940*	17490*	Lugo 1992
	Clay	0-10	18.5	11630*	1690*	26250*	3630*	8870*	
	Tropohumult/clay loam	0-30	11	4923*	10	213	1153	665	Cuevas et al. 1991

+: Obtained by combining average bulk density data from the present study with analyses of 25 soil profiles made in the Nabou forest estate by Leslie et al. 1985; *: Total in soil

for 'available' P prevented intercomparison of sites and a major improvement could be made by the introduction of such standard techniques in a plantation forest network.

Part II

Hydrology and Micro-meteorology

Chapter 5

Grassland Hydrology and Micro-meteorology

5.1 Introduction

To quantify the effect of grassland afforestation on catchment water yield, the dry season water use of the grassland will be determined in this chapter, whereas that of the pine plantations will be treated in the following chapters. A summarising discussion will be presented in Chapter 9.

There is very little hydrological or micro-meteorological information available on natural grasslands in the humid tropics. Yet the need for such data is growing as large areas of semi-unproductive grassland are being converted to plantation forest for wood production (Evans, 1992), whereas at the same time natural forests are being converted to pasture land at a high rate, particularly in Latin America (Whitmore, 1990). .

The changes in microclimate associated with land-use conversion (*e.g.* reflected radiation, temperature, humidity) and soils (*e.g.* infiltration capacity; Shukla *et al.*, 1990) will certainly affect evapotranspiration (ET) and the water yield. In areas where rainfall is highly seasonal the distribution of streamflow over the year may change as well, leading to flooding and erosion in areas where the grassland is overgrazed and regularly burned (Andrus, 1986; Bruijnzeel, 1990). and to shortages of water during dry periods after afforestation of such areas (Kammer and Raj, 1979; van Lill *et al.* 1980; Schulze and George, 1987),

There are several factors (*e.g.* net radiation, soil moisture availability, vegetation surface characteristics) that affect ET by vegetation. During the growing season, if soil moisture is not limiting, water use will depend largely on the available energy. Due to the difference in albedo of grasslands (0.16–0.26) and of coniferous forests (0.05–0.15; Arya, 1988) amounts of the available energy will be higher above the forests than above grasslands and forest transpiration rates could therefore be higher than those of grassland under similar climatic conditions. In addition, the higher aerodynamic roughness of forests as compared to grassland results in more efficient vapour transport, especially during rainfall events when the energy for evaporation is supplied by advective cooling of the air mass just above the vegetation rather than by radiation (Rutter, 1967; Pearce *et al.*, 1980). As such, interception of rainfall by forests should be significantly higher than that by grass (Calder, 1979, 1982; Schulze and George, 1987), also because (particularly coniferous) forest tend to have larger leaf surface areas than grassland (Jarvis *et al.*, 1976; McWilliam *et al.*, 1993) . However, no data is yet available on rainfall interception in tropical grasslands. The nearest, perhaps, is the study of rainfall interception in sugar cane in Brazil by Leopoldo *et al.* (1981) who reported an average value of 4% of incident rainfall.

When the climate is seasonal, the grassland vegetation will exhibit a pattern of growth and dieback (which may be genetically rather than just climatically controlled) coinciding with variations in the moisture content of the topsoil where the root density is largest. In the course of the dry season, when topsoil moisture levels drop to wilting point, the above-ground portion of the grassland vegetation dies and the underground parts remains dormant until the start of the next wet season. Naturally, transpiration will be low during the dormant season due to the reduction in the transpiring leaf area, whereas evaporation from the soil is prevented by the isolating capacity of the dead standing crop and litter layer. As the rooting depth of pine trees (1–10 m, Kammer and Raj, 1979) is much larger than that of the grass (<1 m) forest transpiration can be sustained for much longer periods of time during the dry season, even when topsoil moisture levels have dropped below wilting point (Edwards, 1979; Schulze and George, 1987).

The combination of all these factors suggests that higher annual ET rates may be expected for pine forests than for grasslands. In the following I will briefly review the available evidence from the literature on tropical grasslands and effects of afforestation.

The available studies comparing the water use of grassland to that of forest in the tropics deal with man-made pasture lands in Amazonia (Bastable *et al.*, 1993; Wright *et al.* 1992), annually burned grasslands in the Philippines (Baconguis and Jasmin, 1984; Dano, 1990) or grasslands at higher altitudes in Africa (Focan and Fripiat, 1953; Bailly *et al.*, 1974; Blackie, 1979). These studies all considered short grass (height <1 m) which renders their results less applicable to the taller grasslands found in Fiji. Several of these studies were carried out in small catchments and in some cases leakage must have been considerable, leading to unrealistically high ET values (*e.g.* in the Philippine case). Variations in soil type, seasonality of the climate and grass species further complicate the prediction of water use by grass.

Wright *et al.* (1992) calculated the evapotranspiration from regularly burnt pasture land in a large 12-year-old rainforest clearing in Central Amazonia, Brazil, using micro-meteorological techniques. The ground cover consisted for 85% of grass and for 4% of tree stumps and bushes whereas 13% of the soil was bare. Grass height averaged 28 cm and the leaf area index (LAI) was 1.2 m^2 m^{-2}. ET rates were obtained for a 35-day period which included a dry period of 20 days during which soil moisture stress occurred, although this did not result in dying of the grass. Average ET rates decreased from 3.8 mm day^{-1} shortly after a rainfall event to 2.1 mm day^{-1} after 20 dry days with the ratio of ET/E_0 decreasing from 0.7–0.8 in the beginning to 0.5–0.6 for conditions with increasing moisture stress. The surface resistance increased from 150–180 m s^{-1} shortly after rainfall to 240–330 m s^{-1} at the end of the 20 dry days.

Baconguis and Jasmin (1984) measured the streamflow from a 0.95 ha grassland drainage basin in Luzon, the Philippines, over a period of 8 years. The average annual precipitation input was 3129 mm with a corresponding runoff of only 567 mm. This would imply the very high annual ET value of 2561 mm and basin leakage can therefore not be excluded (Bruijnzeel, 1990).

Blackie (1979) monitored rainfall inputs (2062 mm) and streamflow outputs (1008 mm) from a 37 ha highland catchment (catchment M, 2400 m a.s.l.) in Kenya which was covered by grass (*Pennisetum clandestinum*, 33%), bamboo (47%) and a pine plantation (13%) from 1966 to 1973. He reported an average annual ET of 1054 mm over this period compared to an E_0 of 1513 mm.

In the warm-temperate and less humid environment of South Africa, Van Lill *et al.* (1980) reported on a paired catchment study where decreases in streamflow of 300–380 mm year^{-1} were observed on a total rainfall of 1100–1200 mm after the conversion of (pasture) grasslands on shallow soils to *Eucalyptus grandis*. The effect of afforestation on streamflow became apparent in the third year after planting, and the decline in streamflow reached a maximum in the fifth year after planting and remained fairly constant thereafter. The dry season winter flows were reduced by some 100–130 mm and soil moisture storage was not sufficient to meet evaporative demands in this period. These reductions in water yield were comparable to those observed after afforestation with pine species elsewhere in South Africa (Van Wijk, 1977). Bosch (1982) showed that ET from former grasslands areas afforested with pines in South Africa increased with age of the forest, with maximum increases of 300–450 mm year^{-1} at age 15–25 years. The effect of afforestation was largest on low flows and reductions of around 50% were observed in catchments planted to *Pinus radiata* (Banks and Kromhout, 1963) and *Pinus patula* six to eight years after planting (Bosch, 1979). In a paired catchment study involving small (<40 ha) *Themeda triandra* grassland catchments with shallow soils which were planted to *Pinus patula*, *Pinus radiata* and *Eucalyptus grandis* Smith and Scott (1992) observed reductions of 40 to 60% in low flows after afforestation with pines within 6–8 years after planting. Even higher reductions (90–100%) were observed for the catchments planted to eucalypts, indicating that the water use is also species dependent, at least during the first eight years after planting.

Bosch and Hewlett (1982) reviewed 94 catchment studies world-wide in terms of effects of afforestation and deforestation on water yield. They concluded that water yield reductions after afforestation increased with increasing annual rainfall totals, as well as with the growth rates (age) of the forest.

The only available study on the effect of converting grasslands to *Pinus caribaea* forest in Fiji is the work of Kammer and Raj (1979) However, the study was based on incidental measurements of minimum flows made in the Varaciva, Teidamu and Vitogo catchments between 1969 and 1979, rather than a rigorous comparison of catchment water yield. The forest cover of the Teidamu catchment (55.4 km^2, elevation 10–600 m a.s.l.) increased from less than 10% in 1969 (very young pines) to 60% in 1978, which corresponded with a decrease in minimum flows in the order of 50%. The Varaciva catchment (29.6 km^2, elevation 60–600 m a.s.l.) was completely under forest in 1979 (6–7 year old pines) and a reduction of 65% had been observed for the minimum flows after 1974. Total rainfall measured in the adjacent lowlands at Drasa between April 1978 and December 1979 was 45% below average and minimum flows in the Vitogo catchment (46.9 km^2, only 10% forest cover) decreased as well, particularly from October 1977 onwards. However, as the rate of decrease in minimum flows from the Vitogo catchment was less pronounced than those observed for the Varaciva and Teidamu catchments, the below-average rainfall in 1978 and 1979 will have accounted for only part of the reduction in the minimum flows in the forested catchments.

In the following the water use of a *Pennisetum polystachyon* grassland during the dry season of 1991 will be discussed.

5.2 Field Instrumentation and Methods

Dry season ET of the Nabou grassland was evaluated by:

1. The soil water depletion method at times with a divergent zero-flux plane (Cooper, 1979; Wellings and Bell, 1980)
2. The Penman-Monteith evapotranspiration model (Monteith, 1965)

Daily rainfall (9:00 h) was measured with a standard gauge at Nabou station situated some 100 m from the site. No attempts were made to measure rainfall interception from grassland due to time and material constraints. However, as detailed in Section 5.5, an attempt was made to model this component.

A capacitance soil moisture probe (Didcot Instruments Co. Ltd.) was used to measure profiles of **volumetric soil moisture content** (θ). Two access tubes (G1 and G2) were installed 6 m apart to a depth of 1.2 m on March 28 and April 24, 1991 respectively. Both tubes were installed carefully to avoid damage to the surrounding grass but in order to gain access to the tubes it was inevitable that some of the surrounding grass had to be removed. Details of the measurement procedures and probe calibration are given in Appendix 24. Soil moisture profiles at 2 cm depth intervals were frequently measured (*e.g.* at least once a week) until October 4, 1991. ET was calculated as the total soil moisture loss above a divergent zero flux plane during periods without drainage (Cooper, 1979; Wellings and Bell, 1980). For this the following conditions had to be met:

- No redistribution of moisture within the profile
- Development of a zero flux plane (as indicated by zero moisture loss)
- No significant rainfall between two consecutive measurements

Small amounts of rainfall (amounts <4 mm between two consecutive measurements were found not to influence the moisture profiles) were added to ET as all of this would have been intercepted by the grass cover and litter layer.

A ceramic cup tensiometer was installed close to access tube G1 on June 18 with the cup at a depth of 20 cm to provide information on **soil moisture tension** in the topsoil. The soil moisture tension was read regularly with an electronic pressure transducer connected to a hypodermic needle which was inserted into the tensiometer through a rubber septum. Soil moisture tensions could be measured in this way to the nearest cm up to a tension of 900 cm H_2O (pF= 2.9).

Wet season micro-meteorological measurements were made in a grassland site of limited areal extent on a ridge top close to the Oleolega catchment (Figure 3.4) between January 30 and April 12, 1991. A meteorological mast was erected and equipped with the following instruments.

Solar radiation ($R_s \downarrow$) was measured at 4.65 m above the soil surface with a pyranometer (Skye Instruments Ltd. SP-1110) mounted on a support arm extending 0.8 m from the mast. Care was taken that the instrument was placed horizontally and that the shadow of the mast could not interfere with the measurements. Calibration of the pyranometer by the manufacturer referred to solar radiation in the 300–3000 nm waveband, with absolute errors <5% and typically much better than 3%.

The **incoming and reflected ($R_s \uparrow$) radiation** in a waveband of 300–2500 nm were measured with an albedometer (Kipp & Zonen, Model CM-7). The albedometer was placed level at 4.25 m above the soil surface on a 1–m boom extending from the mast in such a way that the shadow of the mast would not interfere with the $R_s \downarrow$ measurements. Both sensors were recalibrated as the instrument had been damaged during the passage of cyclone Sina. The upward facing sensor was recalibrated against the pyranometer from January 30 until February 18. Reflected radiation measurements were made until April 9 when the albedometer was inverted until April 12 for calibration of the $R_s \uparrow$ sensor against the pyranometer.

The **soil heat flux** (G) was measured with a soil heat flux plate (Middleton & Co. Pty. Ltd.) placed 2 cm below the soil surface. Care was taken not to disturb the vegetation above the flux plate during installation. The accuracy of the plate was 5%. However, as the soil heat flux is spatially very variable, soil heat flux values may be in error of up to 100%.

Air temperature and **relative humidity** were measured at a height of 4.7 m with a Rotronic temperature and humidity sensor (Rotronic A.G., MP100F) equipped with a dust filter. The probe was placed in a Gill radiation screen (model 41004-5) and extended some 60 cm from the mast. The temperature was measured with a platinum resistance thermometer (PRT) with a measuring range of -40 to 60°C and an accuracy better than 0.2 °C. The long-term stable precision of the PRT was 0.1 °C. The humidity sensor had a range of 0–100% with an accuracy better than 1% and a long term stable precision of 0.5% of the relative humidity. However, at relative humidities above 97% very small changes in temperature could cause condensation on the humidity sensor and readings would not have the normal accuracy. Apparent relative humidities in excess of 100% were experienced during rainfall and at night. When this occurred the relative humidity was set at 100%.

Wind speed was measured at 5.0 m with a cup anemometer (Vector Instruments, A101M/L) mounted on a support arm pointing towards the main wind direction (SE). The anemometer has a stalling speed of 0.15 m s^{-1} and could measure wind speeds of up to 75 m s^{-1}. The accuracy was 1–2% of the wind speed according to calibration graphs. No corrections were made for overspeeding or stalling.

Wind direction was measured with a potentiometer type windvane (Vector Instruments, W200P) placed on top of the mast (5.2 m) from February 18 onwards. The fin movement of the windvane had a treshold at 0.6 m s^{-1} and an accuracy of $\pm 1°$. The resolution was 0.3°. As it was difficult to align the arrow on the windvane exactly to the true North, a systematic error of some 5° might have been introduced.

Soil temperatures were measured close to the heat flux plate with two thermistors (Campbell Scientific Ltd. 107B) placed at 2 cm and 10 cm below the soil surface. The accuracy of the thermistors was typically better than 0.2 °C.

All instruments were connected to a Campbell 21X micrologger (Campbell Scientific, Inc.). Measurements were made every 15 seconds and averaged over 15 minutes. The 15-minute averages and standard deviations were temporarily stored on a Campbell Scientific SM726 storage module and later transferred to floppy disk.

Dry season micro-meteorological and hydrological measurements were made in the grassland plot near Nabou station from May 10, 1991, when the grass started to die off, until September 21 when most of the grass had died.

Short-wave radiation was measured by an actinograph (SIAP, type SO-2870), which had been calibrated against the pyranometer, placed at a height of 5.5 m above the soil surface. However, as the calibration of the actinograph proved to be troublesome, the measurements of the Skye pyranometer, which in the meantime had been installed above a mature pine forest 4 km SW of the grassland (Koromani forest plot), were used in the calculations of evapotranspiration. Data from the actinograph were used for the period August 23–26 when all micro-meteorological data were lost in the Koromani forest plot due to a power failure. The 30-minute averages of $R_s \downarrow$ as measured with the pyranometer were averaged to obtain 2-hourly averages.

The **net radiation** (R_n)is defined as the sum of incoming long-wave and short-wave radiation minus the sum of outgoing long-wave and short-wave radiation (Section 7.5.2, Equation 7.8). The net radiation is usually positive during the day when the solar radiation component dominates, and negative at night (no short-wave radiation) when the terrestrial long wave radiation is dominating (Brutsaert, 1982). R_n was measured above the grass on four days in June and July with a portable net radiation indicator (C.W. Thornthwaite Associates, model 603), which was calibrated against the net radiometer (Radiation and Energy Balance Systems) mounted next to the pyranometer at the forest site. Manual readings of R_n in the grassland were taken every 15 minutes from 9:00 h until 18:00 h at a height of 2.2 m.

Temperature and **relative humidity** were measured at a height of 5.5 m with a thermo-hygrograph (Lambrecht, type 252-Ua) housed in a Stevenson screen. The weekly temperature and relative humidity charts were processed to obtain two-hourly averages. Temperatures given by the thermo-hygrograph were calibrated against a station thermometer and against minimum and maximum thermometers (Lambrecht) housed in the same screen. The relative humidity readings of the instrument had been calibrated earlier against humidity measurements by the Rotronics in the Tulasewa forest plot.

Wind speed and **direction** were measured at a height of 5.9 m with a mechanical wind recorder (Lambrecht GmbH). Hourly averages of wind speed and direction were averaged to two-hourly means.

An automatic porometer (Delta T Instruments, model MK3) was used to determine half hourly values of **stomatal resistance** (r_{st}) of water stressed grass leaves at three levels in the canopy. Measurements were made on four days between June 18 and July 23, 1991 from 9:00–10:00 h until 19:00 h. No early morning measurements could be made due to the presence of dew on the grass leaves. The grass canopy was divided into three levels, a lower level from 0–0.7 m, a middle level from 0.7–1.4 m and an upper level from 1.4–1.8 m. The stomatal resistances of five marked leaves within each level were measured at 30–60 minute intervals. Water stress causes a gradual increase in the daytime stomatal resistance up to a point where all stomata are closed as the soil moisture status approaches wilting point (Rutter, 1975). The grass had experienced severe water stress before June 18 and was dying as indicated by the presence of many yellow leaves on the plants. Most remaining green leaves above a level of 1.4 m in the canopy had yellow tips. The vegetation deteriorated fast as the dry season progressed and on July 23 it was very difficult to find any fresh leaves at all above a height of 1 m, whereas most of the leaves below this level had turned yellow or were dead. No attempts were therefore made to measure r_{st} after this date.

The porometer was calibrated at the beginning of each measurement cycle using a calibration plate with known diffusion resistances. The relative humidity range of the porometer was set as close to the actual relative humidity as possible. Stomatal resistances were calculated from the porometer transit times (counts) following the procedure described by Monteith (1988). However, the constants for the extremes of the calibration plate as used by Monteith (1988) were not included in the regressions of transit time on diffusion resistance as they often deviated considerably from the measured values. The actually measured transit times for these extremes were used instead.

The surface resistance (r_s) characterizes the physiological control of water loss by the vegetation and depends on the bulk stomatal resistances of the individual leaves and on the area of the transpiring surface as represented by the leaf area index (LAI)

Table 5.1: *Long-term average monthly rainfall totals (1980–1991) and monthly rainfall totals (mm) for the dry season of 1991 recorded at Nabou station.*

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Nabou, 1991	183	108	27	25	56	60	152	80	691
Nabou, 1980-1991									
Average	240	162	78	72	57	67	74	80	830
Std.Dev.	164	133	107	61	38	48	53	50	

with r_s approximately equal to r_{st}/LAI (Rutter, 1975) . The stomatal resistance depends on several meteorological parameters (*e.g.* radiation, vapour pressure deficit) as well as on the availability of moisture in the soil. When the vegetation is wet, evaporation occurs directly from the leaf surfaces and r_s is zero (Monteith, 1965). When soil moisture is not limiting, stomatal resistances exhibit a diurnal pattern with high nighttime resistances (stomata closed) and low daytime resistances (stomata opened) with a minimum around noon.

5.3 Grassland Hydrology

Monthly rainfall totals for the dry season of 1991 and long-term monthly averages and standard deviations (1980–1991) for Nabou station are shown in Table 5.1. Rainfall totals in 1991 were below the long-term means from April until June and very close to those for July and August. September experienced much higher rainfall than the long-term mean, but all rainfall occurred in the second week of the month (Figure 5.2). Total rainfall between March 29 and October 4 amounted to 428 mm which was 16% below the long-term mean for this period (510 mm).

Estimates of grassland evapotranspiration for selected periods during the dry season were obtained from repeated measurements of soil moisture profiles (ET_{sm}). Three soil moisture profiles, as measured with the capacitance probe in access tubes G1 and G2 on July 8, August 12 and August 19, are shown in Figure 5.1. Similar profiles were observed throughout the study. The July 8 profile was measured two days after a rainy period during which 52.3 mm of rainfall was recorded. The soil moisture tension at a depth of 20 cm was 64 cm H_2O (pF= 1.8). Only little rainfall (3.4 mm on July 27) was recorded until August 17 and the soil dried out accordingly as shown by the profile measured on August 12. The tension in the topsoil increased to values above 1000 cm H_2O (pF= 3) after July 29. Another 59.9 mm of rainfall was recorded between August 17 and 19 resulting in increased θ levels as illustrated by the August 19 profile. The corresponding tension at this date was 56 cm H_2O (pF= 1.7). It is clear from Figure 5.1 that soil moisture fluctuations in the root zone (0–65 cm), where moisture is removed by both evapotranspiration and drainage, are much larger than those below the root zone where moisture is removed by drainage only. Figure 5.2 shows the time series of the average moisture content within and below (65–110 cm) the root zone for access tubes G1 and G2 and the corresponding daily rainfall amounts. The average range in θ was 0.056(±0.030) m^3 m^{-3} in the root zone and 0.037(±0.007) m^3 m^{-3}

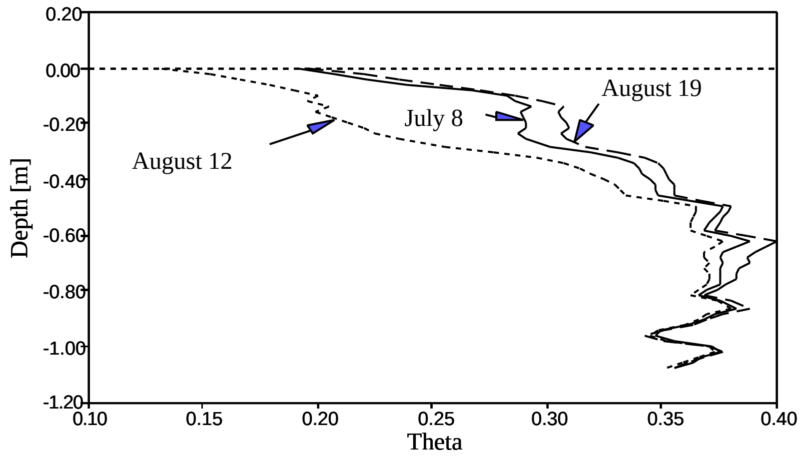


Figure 5.1: *Changes in grassland soil moisture profiles at Nabou during the dry season of 1991 in response to rainfall and drought.*

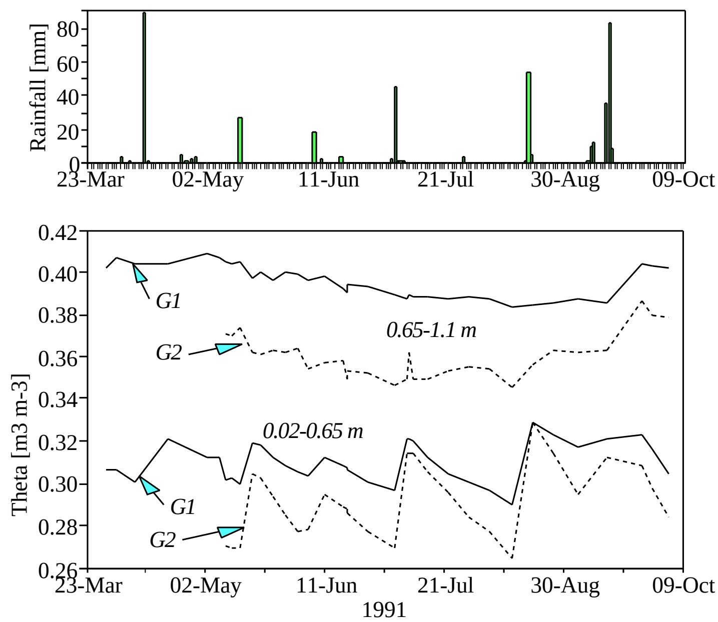


Figure 5.2: *Daily rainfall amounts and changes in θ with time as measured within (2–65 cm) and below the root zone (65–110 cm) in the Nabou grassland plot during the dry season of 1991.*

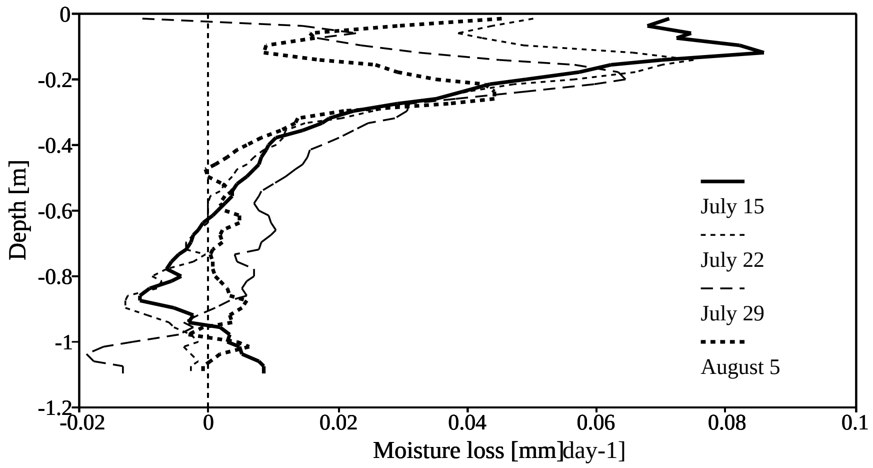


Figure 5.3: *Profiles of moisture loss from the Nabou grassland soil during four consecutive dry weeks in the dry season of 1991.*

below the root zone. The range in θ was largest in the upper 25 cm of the soil where the largest concentration of roots occurred. Soil moisture levels below the root zone showed a gradual decrease from May until August with only small fluctuations in response to rainfall, and increased again to wet season levels after large showers occurred in August and September. The slow changes observed in the moisture profiles below the root zone were consistent with the low unsaturated hydraulic conductivity of this zone (Section 4.3.3).

Soil moisture depletion profiles were calculated from the change in θ between consecutive measurements for each 2 cm depth interval. The change in θ was converted to depths of water (mm) by multiplication with the length of each interval (20 mm) and dividing by the time (in days) between measurements to obtain a moisture loss in mm day^{-1}. The loss was considered positive when moisture was removed and negative when moisture was added. Figure 5.3 shows several moisture loss profiles for the dry period between July 10, shortly after rainfall occurred, and August 5. As indicated earlier, the only rainfall (3.4 mm) within this period occurred on July 27. Throughout the study period similar profiles were observed during dry weather. Moisture losses were close to zero between 50 and 70 cm and a zero flux plane was considered to have developed around a depth of 65 cm. Whenever such a zero flux plane was present all moisture transport above this level was considered upwards as a result of evapotranspiration. Fluxes of moisture below this level were considered downwards as a result of drainage (Cooper, 1979; Wellings and Bell, 1980. The total amount of moisture removed by evapotranspiration (ET_{sm}) was calculated as the sum of the losses for each 2 cm interval above the zero flux plane. As the soil dried the level at which the maximum loss occurred moved downwards from 14 cm on July 15 to 26 cm on August 5. The loss from the upper few cm of soil became negative on July 29 in response to rainfall on July 27. The resulting increase in θ caused a higher moisture loss at this depth during the following week (August 5).

Divergent zero flux planes developed on 59 days around access tube G1 and on 91 days around access tube G2. The resulting average ET_{sm} rates were 0.7($\pm$0.2) mm day^{-1} and 1.1(±0.3) mm day^{-1} respectively. The average ET_{sm} rate for both tubes therefore amounted to 0.9(±0.2) mm (n=59).

It is not known to what extent the removal of grass on one side of the access tubes has influenced the rates of ET_{sm}. However, the depth of the observed zero flux planes corresponded well with the rooting depth of the grass and the root system surrounding the tubes may not have been affected too much. The high spatial variability of the measured ET_{sm} rates indicated that the presently obtained values may well be several tenths of mm's in error.

5.4 Grassland Micro-meteorology

The temporal resolution of evaporation estimates via hydrological methods is often low, ranging from about 1 day when in the case of soil moisture measurements to a season or year for catchment water balance studies (Ward and Robinson, 1990). The zero flux plane method gave ET_{sm} values for selected dry periods only and the temporal resolution depends therefore on the time elapsed between consecutive soil moisture measurements, which was in the order of a week during the present study. The resolution of micro-meteorological methods is much higher and depends largely on the sample frequency of the necessary meteorological parameters. However, micro-meteorological methods have their own flaws as their use is more or less restricted by the underlying theory which applies for "ideal terrain" only (*e.g.* flat, homogeneous terrain with a large fetch; Thom, 1975). In addition, it is difficult to derive surface dependent parameters as roughness length, displacement length, aerodynamic resistance and surface resistance without an elaborate micro-meteorological set-up (Shuttleworth, 1988). As such a set-up was not feasible for the grassland study, several assumptions had to be made with respect to surface characteristics to calculate daily evapotranspiration rates with the Penman-Monteith model.

5.4.1 Radiation and Soil Heat Fluxes

Daily short-wave radiation totals at the Oleolega catchment site averaged 20.10 (±4.26) MJ m^{-2} day^{-1} in February and 18.58 (±4.98) MJ m^{-2} day^{-1} in March, with corresponding reflected radiation totals of 3.61 (±0.74) MJ m^{-2} day^{-1} and 3.47 (±0.92) MJ m^{-2} day^{-1}. The mean diurnal variations in incoming and reflected short-wave radiation in March are shown in Figure 5.4. Similar patterns were observed in February.

Daily average values of wet season albedo were 0.180 (±0.008) and 0.187 (±0.007) for February and March, respectively. These values are similar to reflection coefficients derived for Amazonian pasture (0.163; Bastable *et al.*, 1993) and various West African savannas (0.17–0.22: Oguntoyinbo, 1970; 0.17–0.20: Montény and Gosse, 1976). The diurnal variation in albedo was calculated from 15-minute daytime averages ($R_s\downarrow$>100 W m^{-2}, n= 2730) of $R_s\downarrow$ and $R_s\uparrow$ and is shown in Figure 5.5. The treshold value of 100 W m^{-2} coincided with an average solar altitude of 16°, whereas elevation of the sun at noon ranged from 90° on January 30 to 67° on April 4. The albedo averaged 0.181(±0.006) between 9 am and 5 pm and had a noon minimum of 0.175(±0.006). Early morning values of the albedo were very low, with a minimum of 0.13(±0.05) (n= 43) at 7:15 h, and increased to a maximum of 0.20(±0.08) (n= 65) at 8:30 h (Figure 5.5). The diurnal pattern showed a typical dish shape from 8:30 h onwards. Similar early morning variations were observed by Oguntoyinbo (1970) for grasslands

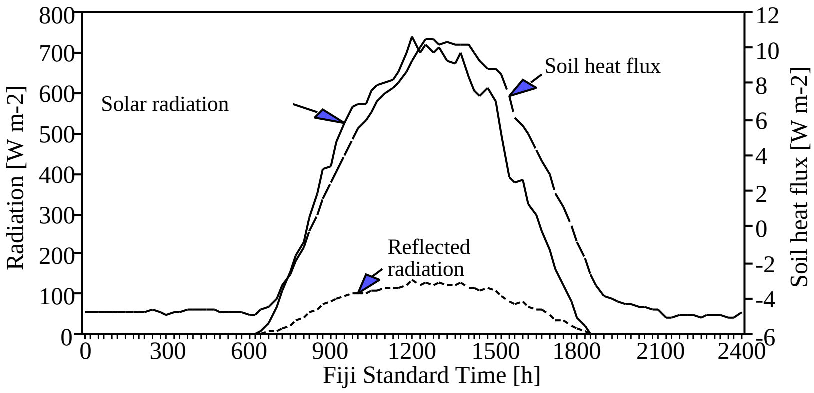


Figure 5.4: *Mean diurnal patterns of solar radiation, reflected short-wave radiation and soil heat flux at the Oleolega catchment in March 1991.*

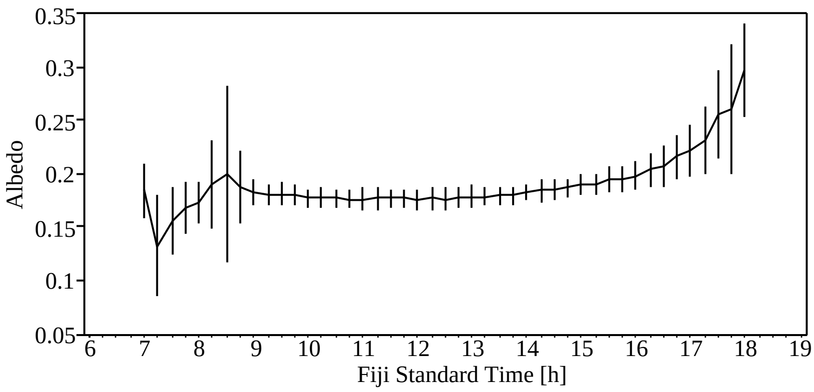


Figure 5.5: *Diurnal course of the albedo for grassland at the Oleolega catchment during the wet season of 1991.*

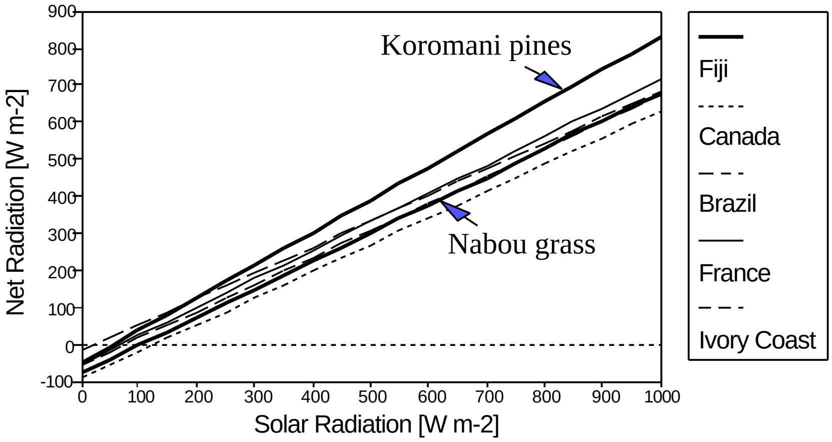


Figure 5.6: *Regressions of daytime* $R_s \downarrow$ versus *on* R_n *for grasslands in the temperate zone and in the humid tropics. The regression line calculated for the Koromani pine forest is shown for comparison.*

in Nigeria, who suggested that dew deposition on the leaf surfaces might reduce the reflectivity by trapping radiation. The grasslands in Nabou were often wet in the early morning due to the deposition of dew and the relatively large standard deviations observed between 8:15 h and 8:45 h could therefore be explained by the changes resulting from the transition from a wet surface to a dry grass surface.

An empirical relation (Equation 5.1) was established between daytime R_n measurements made above grass and corresponding $R_s \downarrow$ measurements near the Koromani forest plot using linear regression analysis. The data set consisted of 26 half-hourly radiation averages collected under clear sky conditions with $R_s \downarrow$ ranging from 86 W m^{-2} to 760 W m^{-2}. The corresponding R_n values ranged from -19 W m^{-2} to 474 W m^{-2}.

$$R_n = -77.7(\pm 27.2) + 0.76(\pm 0.03) R_s \downarrow$$
$$\text{n}= 26,\ \text{r}^2 = 0.98 \tag{5.1}$$

The regression line is shown in Figure 5.6 together with those published for other tropical grasslands in Ivory coast (Montény & Gosse, 1976), Central Amazonia (Bastable *et al.*, 1993) and temperate sites in Canada (Ripley & Redman, 1976) and Southern France (Pers. comm. N.J. Bink), despite the fact that observations at the other sites pertained to much shorter grass, and although the presently obtained regression constants were calculated from relatively few clear sky measurements of R_n and $R_s \downarrow$, they fall within the range of those published for the other grassland sites adding confidence to the results. Equation 5.1 was therefore used to calculate R_n for grassland at Nabou during the dry season of 1991 from half-hourly averages of $R_s \downarrow$ measured above Koromani forest. The regression line for a nearby mature pine forest (Koromani forest, Section 7.5.2) is shown in Figure 5.6 to illustrate the difference between the two vegetation types.

Daily totals of the heat flux into the soil (G) amounted to 0.02($\pm$0.10) MJ m^{-2} day^{-1} and -0.00$\pm$0.10 MJ m^{-2} day^{-1} in February and March, 1991, respectively, with

Table 5.2: *Ranges and averages (standard deviation between brackets) of minimum and maximum temperature (° C) and relative humidity (%) measured above the Nabou grassland plot during the dry season of 1991 (n is the number of days).*

	T	Tmin	Tmax	n	RH	RHmin	RHmax	n
Range	19.0-25.9	11.7-24.9	20.9-32.9	127	61-98	42-90	61-100	124
Average	22.5 (1.6)	17.9 (3.0)	28.2 (1.9)	127	83 (6)	59 (9)	98 (6)	124

a minimum value of -0.25 MJ m^{-2} day^{-1} and a maximum of 0.22 MJ m^{-2} day^{-1}. The soil heat flux was low compared to the radiation inputs and the positive value in February indicated a net warming up of the soil. The observed minimum and maximum values of G were -13.9 W m^{-2} and 19.1 W m^{-2}. It was not possible to measure G during the dry season (because the instruments were in use at the Koromani site by then), and a relationship was established between 15-minute averages of daytime solar radiation ($R_s \downarrow > 50$ W m^{-2}) and corresponding values for G, measured in February and March:

$$G = -1.24(\pm 3.15) + 0.015(\pm 0.002) R_s \downarrow$$
$$\text{n}= 2802,\ \text{r}^2 = 0.65 \tag{5.2}$$

Although it is very likely that the regression constants will show a seasonal variation with positive monthly soil heat flux totals during the wet season (warming up of the soil) and negative totals during the dry season (cooling down of the soil), the variation will presumably be small in densely vegetated grassland areas where there is no direct radiation on the soil. Hence Equation 5.2 was used to calculate dry season values of G.

5.4.2 Temperature and Humidity

Diurnal patterns in temperature and humidity above the Nabou grassland plot were similar to those shown in Section 2.4.2 for Nadi. As the establishment of forest plantations is likely to alter the temperature and humidity regimes average dry season minimum and maximum temperatures and relative humidities will be presented in this section, whereas those measured above Koromani forest during the same period are presented in Section 7.4. The averages and ranges of the temperature and relative humidity at the Nabou grassland site are given in Table 5.2

5.4.3 Wind speed and Direction

Windspeeds during the dry season were low with a mean of 2.1($\pm$0.9) m s^{-1}. The maximum 2-hourly average of recorded wind speed was 7.2 m s^{-1}. Wind speeds were usually even lower at night (1.2($\pm$0.8) m s^{-1} between 18:00 h and 6:00 h) and increased during daytime (2.9($\pm$1.1) m s^{-1} between 6:00 h and 18:00 h). The wind direction was predominantly southeast.

5.4.4 Surface Resistance and Derived Estimates of Evapotranspiration

To derive daily ET rates for the grassland, use was made of the Penman-Monteith equation (Monteith, 1965):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho c_p \; \delta e / r_a}{\Delta + \gamma(1 + r_s/r_a)} \tag{5.3}$$

where ρ and c_p represent the density and the specific heat of air, respectively, δe the vapour pressure deficit, Δ the change of the saturation vapour pressure with temperature and γ the psychrometric constant. Formulas for their calculation have been presented in Appendix 22.2. ET$_{sm}$ was taken as a reference to derive representative values for the surface (or canopy) resistance r_s, which was thought to increase with the progress of the dry season as a result of the dying off of the grassland vegetation.

The aerodynamic resistance (r_a, in s m^{-1}) was calculated from wind speed measurements using Equation 5.4 (Thom, 1975) which holds under neutral atmospheric conditions.

$$r_a = \frac{\left(\ln \frac{z-d}{z_0}\right)^2}{k^2 \cdot u_z} \tag{5.4}$$

In this equation z represents the heigth of the wind speed measurements (5.9 m), z_0 and d are surface roughness parameters, k is the von Karman constant (taken as 0.4) and u_z is the wind speed as measured at height z. The surface roughness parameters (z_0 and d) depend on the height, density and flexibility of the vegetation and are usually obtained from above-canopy wind profiles (Thom, 1975). However, these were not available for the grassland during the present study and the roughness length (z_0) and the displacement length (d) were estimated using empirical expressions relating z_0 and d to the average height of the vegetation (h). The ratio of z_0 to h ranges from 0.02 to 0.2 (Garratt, 1977) and was taken as 0.12, whereas the ratio of d to h averages between 0.7 and 0.8 for most vegetative canopies (Arya, 1988) and was taken as 0.75. The average grass height decreased from 1.9 m in May to 1.2 m in September and z_0 and d decreased correspondingly from 0.23 m and 1.43 m to 0.14 m and 0.9 m respectively.

Daily averages of r_{st} for the various levels in the canopy are shown in Table 5.3 together with the corresponding soil moisture tension. Although soil moisture was not really limiting on the days of measurement, as indicated by the pF values, mean daytime r_{st} values were high at 170–330 s m^{-1} above a height of 0.7 m and 1001–1522 s m^{-1} between ground level and 0.7 m. The stomatal resistances above a height of 0.7 m were relatively low on July 10, possibly in response to increased soil moisture levels (pF= 2.0) as a result of rainfall during the first week of July. The stomatal resistance varied considerably during the day (Figure 5.7) but showed no correlation (r^2= 0.01) with irradiance, as illustrated in Figure 5.8, nor with any other micro-meteorological parameter (*e.g.* vapour pressure deficit). This inability of the stomata to respond to changes in microclimate is not surprising in view of the poor condition of the dying vegetation.

With little variation in daily means of r_{st}, LAI became the single most important factor determining the change in the magnitude of r_s during the dry season. The LAI decreased from 1.3 m^2 m^{-2} in May to 0.2 m^2 m^{-2} in September (Section 10.3) and daily LAI values were calculated with Equation 5.5, which was obtained by linear

Table 5.3: *Average stomatal resistances (s m^{-1}) of grass blades at various heights in the grass cover and those measured on needles of a nearby isolated pine tree. The pF represents the soil moisture tension at the time of the measurements, SD is the standard deviation.*

Date	June 18		June 25		July 10		July 23	
Time	9:30-17:30		10:30-18:30		10:30-18:00		11:30-18:00	
pF(20 cm)	2.6		3.0		2.0		2.6	
Grass	Avg	SD	Avg	SD	Avg	SD	Avg	SD
1.4-1.8 m	214	76	211	33	187	28	239	55
0.7-1.4 m	330	156	312	80	197	33	242	72
0.0-0.7 m	1246	553	1585	548	1674	1150	1239	443
Time			11:00-17:00		11:00-17:00		12:00-17:00	
Isolated pine tree			225	30	231	29	258	54

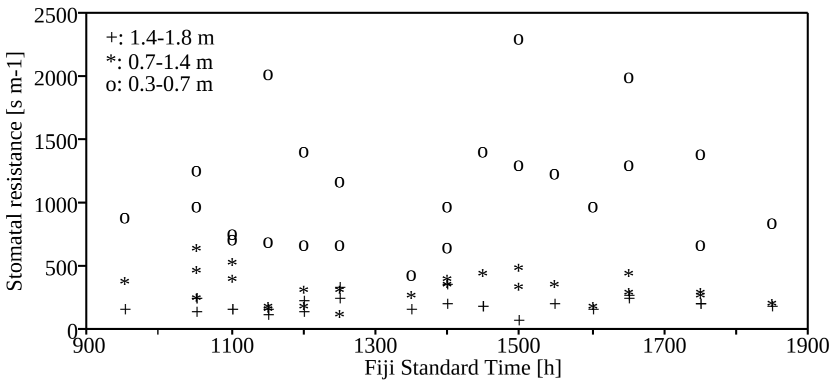


Figure 5.7: *Diurnal variation of r_{st} of grass leaves at different heights in the Nabou grassland plot during the dry season of 1991.*

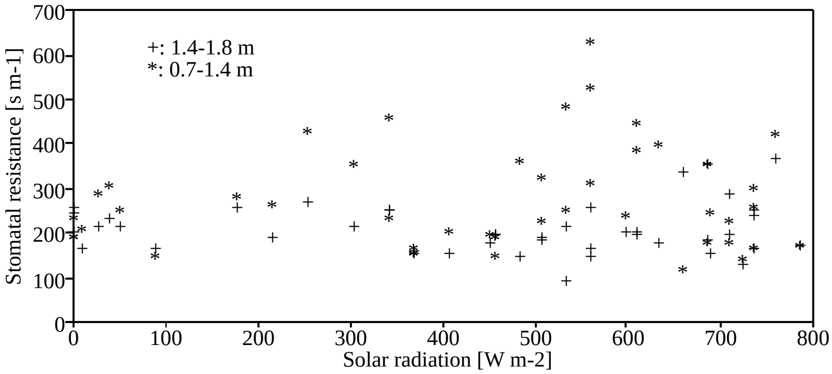


Figure 5.8: *Variation of r_{st} with solar radiation at the Nabou grassland plot during the dry season of 1991.*

regression analysis of the LAI data (n= 3) against julian day (JD).

$$\mathrm{LAI} = 2.5 - 0.009 * \mathrm{JD}$$
$$\mathrm{r}^2 = 0.98,\ 130 < \mathrm{JD} < 263 \qquad (5.5)$$

To smooth the transition from daytime (8:00–18:00 h) to nighttime (18:00–8:00 h) conditions (stomatal closure), nocturnal values for r_s were arbitrarily set at $1000 * e/e_{sat}$ and ranged from 500 to 1000 s m^{-1}. During rainfall events and shortly thereafter r_s was set to zero (Monteith, 1965).

Due to the difference in time resolution between the Penman-Monteith equation used in the present study (2 hours) and the soil water depletion method (several days) daytime values for r_s had to be derived by trial and error. Estimates of daytime r_s were inserted in the Penman-Monteith formula and the sum of the resulting 2-hourly ET_{pm} values over seven selected periods spanning 48 days were compared with the corresponding ET_{sm} values. The fitted r_s was low in May (79 s m^{-1} for the period May 20–24) and increased to values between 300 s m^{-1} and 400 s m^{-1} for August and September. Linear regression analysis using data on r_s and LAI for the selected periods resulted in Equation 5.6 which describes the relation between LAI and r_s for daytime conditions.

$$r_s = 441(\pm 79) - 282(\pm 112) * \mathrm{LAI}$$
$$\mathrm{n}= 7,\ \mathrm{r}^2 = 0.56 \qquad (5.6)$$

Daytime r_s values for the dry season calculated with Equation 5.6 ranged from 76 s m^{-1} in May to 390 s m^{-1} in September.

Daytime r_s values for May and June, when the grass started to die off, were within the general range for grass (60–200 s m^{-1}) given by Rowntree (1990) and similar to the values reported by Wright *et al.* (1993) for Amazonian ranchland (160–330 s m^{-1} at LAI= 1.2). De Bruin *et al.* (1991) observed r_s values between 30 and 100 s m^{-1} for short (40 cm) irrigated grass in the South of France, whereas much higher values were observed in an adjacent non-irrigated area which was sparsely vegetated with herbs.

The high values presently derived for August and September are not unrealistic in view of the fact that most of the vegetation had died by then. The fit between ET_{sm}

and ET_{pm} for the selected periods was good with a difference of only 0.6% between total ET_{sm} and total ET_{pm} over 47 days. Daily ET_{pm} values were subsequently calculated for the period of May 11 until September 19 (131 days) using Equation 5.6. As the wind speed record was slightly shorter than that for the other meteorological parameters, wind speeds measured above Koromani forest were used for the missing period (6 days). The error introduced in this way was assumed negligible as wind speeds measured above grassland and forest were comparable. Total ET_{pm} for the 131-day period amounted to 127.7 mm (40% of total rainfall) and averaged 0.97(±0.34) mm day^{-1}.

The Penman open water evaporation (E_0, Appendix 22.2) was calculated from daily radiation totals and averages of temperature, relative humidity and wind speed. The ratio of actual sunshine hours to the day length (n/N) was calculated from the radiation record using the relations given in Section 2.4.3. E_0 amounted to 485 mm for the period under consideration (n= 131), with a daily mean of 3.7(±1.0) mm day^{-1}. Daily rainfall totals as well as changes in E_0, ET_{pm} (24-h totals) and ET_{sm} with time are given in Figure 5.9. The ratio of ET_{pm} to E_0 was low and decreased from 0.32±0.11 in May to 0.25(±0.12) in September with a minimum of 0.21(±0.09) in August. The decrease in ET_{pm}/E_0 was attributed to the gradual dying of the grass as the dry season progressed. The evapotranspiration rates presently found for grassland will be compared with those of the pine forests in Chapter 9.

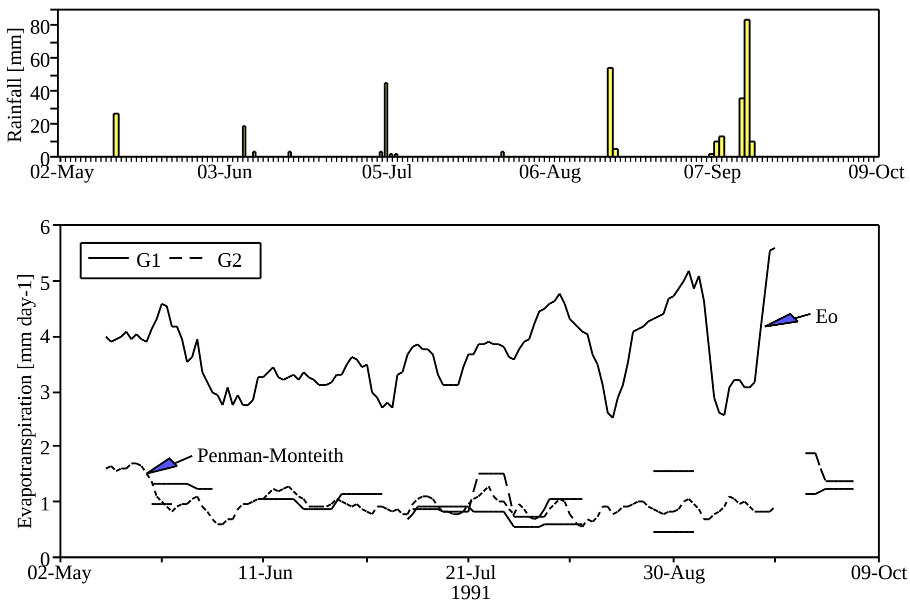


Figure 5.9: *Daily rainfall totals and the course of evapotranspiration in Nabou grassland with time during the dry season as based on soil water depletion rates, and the Penman-Monteith model. The Penman open water evaporation has been added for comparison (ET_{pm} and E_0 smoothed using 5-days moving averages).*

5.5 Modelling of Grassland Interception Loss

Like transpiration, interception of rainfall by grass and litter is likely to show a seasonal variation as well in correspondence with the seasonal changes in grass biomass and litter mass. An attempt was made to quantify the interception loss during the dry season of 1991 (May–October) from daily rainfall totals using the models described in Sections 6.4.1 (Gash analytical model; Gash, 1979) and 6.4.2 (This study).

The free throughfall coefficient (p) for grass was determined from gap fraction measurements (Section 10.3) and amounted to 0.79 (as measured 1 m above the soil surface). The grassland canopy storage (S) was assumed to be slightly lower than the post-cyclone value found for for Tulasewa forest (0.3, Section 6.4.1) which was heavily dominated by mission grass by then with only occasional trees remaining, and was set to 0.2 mm. 'Trunk' storage and the proportion of rainfall going to 'trunks' was set to zero. The evaporation rate from a saturated canopy was determined from the micro-meteorological measurements during rainfall using the Penman-Monteith equation (Equation 5.3) with r_s set to zero and amounted to $0.06(\pm 0.03)$ mm h^{-1}. The mean rainfall rate onto the saturated grass cover was determined using hourly rainfall data collected at Koromani forest and amounted to 2.13 mm h^{-1} implying an $\bar{E}/\bar{R}$ value of 0.03.

An estimate of the water holding capacity of the litter layer was obtained from litter samples collected in February 1991. The gravimetric moisture content of the litter was equal to the air-dry moisture content (14% of dry weight) on February 21, after 16 days without significant rainfall. At this stage the litter layer contained 0.1 mm of moisture. The gravimetric moisture content had increased to 161% on February 28, some 10 hours after rainfall had ceased. Since no visible drainage occurred from the litter upon sampling, this moisture content may have been close to the field capacity value with a storage equivalent of 1.7 mm. As such, a minimum of 1.6 mm of water may be available for evaporation after rainfall ceases during the wet season. Applying the above percentages of the maximum and residual moisture contents to the litter biomass observed in May resulted in maximum and minimum moisture contents of 1.0 and 0.1 mm respectively. The May values were used to represent the moisture storage characteristics of the litter layer during the dry season. Evaporation rates from the grassland litter layer were assumed to be equal to those in the forest (Section 6.4.2).

Total rainfall during the period of May 2 until October 1, 1991 amounted to 319 mm. Gash's analytical model predicted a throughfall of 306 mm resulting in an interception loss of 13 mm or 4% of total rainfall for the grass canopy. We have been unable to find comparative information on the interception of rainfall by grass in the tropics. However, the presently obtained value compares well with that measured for sugar cane (which, after all, is a domesticated form of a tall grass species) in Brazil (4.1 % of rainfall; Leopoldo *et al.*, 1981). Derived interception losses from the litter layer were higher than those for the live crop, amounting to 21 mm or 7% of total rainfall. The estimated combined interception loss therefore amounted to 34 mm or 11% of total rainfall. A discussion of the differences in interception losses from grassland and forest will be given in Chapter 9.

Chapter 6

Forest Hydrology

6.1 Introduction

A review of the literature dealing with hydrological effects of the the conversion of grassland to plantation forest has already been presented in the previous chapter. This chapter deals with the quantification of the fluxes of water through several pine plantations within the Nabou forest estate. Quantification of these fluxes is a prerequisite for the determination of the nutrient cycle (Chapter 13), as water forms a prime transport medium in this respect (Likens *et al.*, 1977). Considerable attention will be given to the estimation of interception losses, both from the canopy and from the litter layer. Furthermore, an attempt will be made to obtain forest evapotranspiration rates from changes in volumetric soil moisture contents.

6.2 Field Procedures and Methods

Hydrological measurements were made in the Tulasewa, Korokula and Koromani forest plots. The hydrological instrumentation was similar in each plot and the methods and instruments used are discussed below.

Rainfall stations were located in clearings or grassland close to each of the forest plots. Each station consisted of three manual gauges and a pluviograph, positioned such that there were no obstructions above a maximum angle of 30°. Any surrounding grass was kept short. The dates of installation and removal of the equipment are shown in Table 6.1. A standard rainfall gauge (Lambrecht) with an orifice of 100 cm^2 and a capacity of 150 mm was used as a reference for the calibration of the other gauges. The gauge was mounted on a standard at a height of 1.3 m above the soil surface. Rainfall intensity and duration were measured with a tipping bucket rainfall recorder (SIAP, UM- 8100) with a resolution of 0.4 mm (orifice 607 cm^2) and a temporal resolution of one hour. The pluviographs were placed at a height of 1–1.5 m above the soil surface. A custom-made rain gauge (100 cm^2 orifice) with a capacity of 410 mm was placed close to each standard gauge for calibration purposes. A small piece of filter wool in the outlet of the funnel prevented entering of organic debris and insects. The standard raingauge and the custom-made gauge were emptied at least once a week. The fourth rain gauge was used to collect rainwater samples for chemical analysis and consisted of a plastic funnel (orifice 471 cm^2, height 0.7 m) placed on top of a white PVC cylinder

Table 6.1: *Installation and removal dates of rainfall gauges, throughfall gauges and litter percolation trays in Tulasewa, Korokula and Koromani forests.*

Plot	Code	Rainfall		Throughfall		Litter percolate	
		Start	**End**	**Start**	**End**	**Start**	**End**
Tulasewa Forest	PU 20-2	28-Nov-89	30-Sep-91	30-Nov-89	30-Aug-91	22-Dec-89	30-Aug-91
Korokula Forest	PU 09-5	06-Jan-90	01-Oct-91	08-Jan-90	01-Oct-91	16-Jan-90	01-Oct-91
Koromani Forest	PU 09-4	18-Dec-89	02-Oct-91	23-Jul-90	02-Oct-91	24-Dec-89	02-Oct-91

acting as a radiation shield. The funnel drained into a second container of chemically inert plastic with a capacity of 210 mm of rainfall. The light conditions within the PVC container were low to diminish biological activity (*e.g.* growth of algea) in the collected rainwater. Contamination by insects or organic debris was avoided by a chemically inert 2 mm wire mesh on top of the funnel (coarse material) and a piece of filter wool in the funnel outlet (fine material). The funnel, the inner container and the wire mesh were rinsed with rainwater after samples were collected and the filter wool was renewed.

Throughfall was measured with twenty sharp-rimmed standard gauges in each plot. Their dates of installation and removal are shown in Table 6.1. All gauges were placed on the soil surface with the funnel at a height of 35 cm. The gauges were initially placed at randomly selected gridpoints within a 10 m by 10 m grid and were relocated randomly within a 5 m radius of a gridpoint after each measurement to optimize the representativity of the data (Lloyd and Marques-Filho, 1988). On several occasions not all throughfall gauges could be read due to disturbance by children, stray animals or wind (*e.g.* cyclones), and the average of the remaining gauges was then taken to represent the average throughfall.

Stemflow was measured from October 1990 until August 1991 in the Tulasewa forest plot only. Five trees were equipped with a spiral type PVC gutter after the bark had been removed locally. The gutter was connected to a 4.1 l plastic container. Stemflow volumes (ml) were converted to depths (mm) by dividing by the surface area occupied by each tree on the basis of the initial planting density (9 m^2). Due to the small size of the containers (4.1 l) overflow occurred when rainfall exceeded 16 mm and therefore no reliable estimates were obtained for larger storms.

Litter percolate was measured with four litter percolation trays in each plot. Dates of installation and removal are again given in Table 6.1. Each tray consisted of a shallow (3 cm deep) rectangular hard PVC box (area 2090 cm^2) covered with chemically inert wire mesh (1 mm mesh). Three openings on one side were connected at the downslope end of the plate by PVC tubing to a 4.1 l plastic container, placed in a hole dug into the soil. The trays were carefully inserted below the litter layer (L+F) at a low angle so that percolating water flowed into the container. Filter wool was placed underneath the wire mesh in front of the openings to prevent organic material from entering the container or blocking the tubing. Measurements were made at least once a week. Due to the small size of the container overflow occurred whenever rainfall amounts exceeded 30 mm.

The rainfall, throughfall, as well as small amounts of stemflow and litter percolate were determined with plastic measuring cylinders with a volume of 250 ml or 500 ml. The cylinders could be read with an accuracy of 2 ml (or 0.2 mm for rainfall and throughfall). Larger amounts of litter percolate and stemflow (*e.g.* >2 l) were measured with a 2000 ml plastic measuring cylinder with an accuracy of 10 ml.

The Didcot capacitance soil moisture probe referred to in Section 5.2 was used to measure profiles of **volumetric soil moisture**. Five access tubes were installed in each plot during the dry season of 1990. Depths ranged from 68–118 cm in the Tulasewa forest plot, via 36–70 cm (on bedrock) in the Korokula forest plot to 70–110 cm in the Koromani forest plot. Details on the calibration and measurement procedures are given in Appendix 24.

Ceramic cup tensiometers were used to monitor **soil moisture tensions** in the respective soil horizons. In Tulasewa forest 10 tensiometers were installed around access tube 1 in May 1990 at 10–20 cm depth intervals up to a depth of 1.4 m. At two other locations tensiometer nests consisting of three tensiometers each were installed in June in the A- and B-horizons down to depths of 0.8 m. In Korokula forest six tensiometers were installed close to access tube 1 in June 1990 at 10 cm depth intervals down to 54 cm (bedrock). In Koromani forest six tensiometers were installed in August 1990. The tensiometers were placed close to access tube 4 (midslope) at 15 cm depth intervals down to 80 cm. Soil moisture tensions were read regularly with a custom-made electronic pressure transducer connected to a hypodermic needle which was inserted into the tensiometers through a rubber septum. Soil moisture tensions could be measured up to a tension of 900 cm H_2O (pF= 2.9) and to the nearest cm of tension.

In the Tulasewa forest plot a Scanivalve system (Burt, 1978) has been in operation from June until November 1990 to measure soil moisture tensions on a daily basis. The system consisted of a Scanivalve fluid switch wafer (Scanivalve Corp., model W02 1P-24T) connected to a pressure transducer (Pressure Sensors Ltd. Model MPT-117) and a control unit and datalogger, developed at FES-VUA. The Scanivalve switch was connected to the control unit and all 24 input channels were scanned twice a day within a 60-minute period, allowing 2.5 minute equilibration time for each input channel. The pressure transducer was connected to the datalogger and the data recorded on an audio cassette. The data were later transferred to floppy disc. The system was powered by a 12 V car battery. Two input channels of the Scanivalve were connected to water filled plastic bottles of which the water levels differed by 1.00 m, which were used as a reference (Burt, 1978). Seventeen input channels were connected via copper tubing to tensiometers at various depths. The remaining five channels were not used.

6.3 Rainfall Amounts and Characteristics

The amounts of rainfall recorded at each of the forest plots and at Nabou station during the 21-month period are given in Table 6.2, together with long-term averages for Nabou station (17 years of data). There was no distinct dry season in 1990 as rainfall amounts in June, August and November were well above their long-term averages. The high rainfall amounts recorded during these months were compensated by below average rainfall in April, May and October, resulting in an annual rainfall total close to the long-term average.

During the wet season of 1991 monthly rainfall amounts were close to the long-term average, but lower than average rainfall totals were recorded during the dry season, with the exception of September. Rainfall amounts remained below average until the end of the year and the annual total for 1991 was therefore much lower than average, amounting to 1339 mm at Nabou station (Table 6.2).

Table 6.2: *Monthly rainfall totals (mm) for Tulasewa, Korokula and Koromani forests and for Nabou Station as recorded during the present study, and long-term rainfall totals for Nabou Station (1973–1992).*

Station	Tulasewa Forest		Korokula Forest		Koromani Forest		Nabou station		Nabou 1973-1992	
Year	1990	1991	1990	1991	1990	1991	1990	1991	Average	SD
Jan	254.1	354.2	257.3	231.2	346.8	184.3	250.4	305.8	250.7	*135.5*
Feb	131.1	280.4	145.7	134.8	122.5	147.0	129.0	215.9	281.2	*139.7*
Mar	440.7	370.8	429.2	237.2	468.9	297.8	282.1	187.7	258.6	*185.1*
Apr	91.1	177.1	23.3	117.8	21.1	109.1	41.1	112.3	156.5	*136.8*
May	11.9	20.3	62.0	22.0	56.3	21.8	4.8	29.4	75.7	*93.7*
June	140.0	34.9	148.3	25.3	143.9	37.1	155.8	27.3	73.2	*61.7*
July	54.1	66.7	60.8	49.8	52.4	42.1	72.6	58.7	57.8	*34.3*
August	195.4	56.9	202.4	55.7	196.8	72.7	169.6	63.0	77.8	*67.5*
September	102.0	171.9	104.2	153.3	97.2	147.0	82.4	156.2	78.4	*59.0*
October*	55.3		34.3		49.0		35.7	75.0	108.0	*69.1*
November	437.7		218.7		252.6		213.1	52.6	119.4	*98.9*
December*	199.1		109.8		96.8		87.2	54.6	158.1	*109.8*
Total	**2112.5**	**1533.2**	**1796.0**	**1027.1**	**1904.3**	**1058.9**	**1523.8**	**1156.3**	**1695.4**	*408.9*

*: Underlined values excluded from the total.

The rainfall data presented in Table 6.2 reveal a clear trend with respect to the distance from the coast, with relatively low rainfall near the coast (*e.g.* Korokula site) and increasingly higher amounts more inland (*e.g.* Tulasewa site). However, rainfall also showed a large spatial variation, as shown by the different amounts recorded at Korokula and Koromani rainfall stations, which were less than 4 km apart and both situated close to the coast (Figure 2.2). The temporal variation of rainfall in the tropics is often high where rainfall is convective (Riehl, 1979), resulting in large standard deviations for long-term averages. This is illustrated by the annual totals recorded at Nabou station, which ranged from 826 mm in 1987 to 2498 mm in 1989. Similarly, wet season (November–April) monthly rainfall totals ranged from 4 mm in April 1983 to 658 mm in March 1985, whereas dry season monthly totals ranged from 0 mm in October 1986 and August 1988 to 400 mm in May 1989 (Table 6.2).

Rainfall totals recorded by the pluviograph, the standard gauge, the custom-made gauge and the above-canopy raingauge in the meteorological tower (if present) corresponded very well. Therefore errors in annual rainfall totals for the forest stations are thought to be within 5%. Errors were probably larger for rainfall collected during the passage of cyclone Sina, due to disturbances in the wind fields caused by the hurricane force winds. The low rainfall total recorded at Nabou station in November 1990 (when cyclone Sina passed) compared to those measured at the forest sites may have been caused by the sheltering of the Nabou gauge by nearby buildings located upwind from the gauge.

Short-duration rainfall intensities were obtained from 5-minute above canopy rainfall totals recorded by the micro-meteorological set-ups in the Tulasewa (1990) and near the Koromani forest (1991) plots. The overall maximum intensity (9.9 mm in 5 minutes) was observed above Tulasewa forest on February 16, 1990, during a single

Table 6.3: *Maximum rainfall amounts and intensities for different time intervals as measured above the canopy of Tulasewa forest on February 16, 1990.*

Time interval (minutes)	5	10	15	20	25	30	60
Rainfall amount (mm)	9.9	18.5	25.1	31.2	34.6	36.4	43.2
Rainfall intensity (mm/h)	118.2	110.9	100.5	93.5	83.0	72.8	43.2

afternoon shower which lasted for less than an hour (Table 6.3). The observed rainfall intensities for time periods ranging from 5 minutes to 1 hour are shown in Table 6.3. Extreme rainfall intensities of these magnitude are common in Fiji with return periods of 2 years for the 10-minute and 20-minute intensities and less than 2 years for the 30-minute and 60-minute intensities (Reddy, 1989c). The maximum rainfall intensities observed at Nadi Airport (1951–1988) were 40 mm, 61 mm and 162 mm for durations of 10, 30 and 60 minutes respectively (Reddy, 1989c).

The absolute maximum amount of rainfall recorded in a single hour during the study was 61.2 mm at Koromani forest in the evening of March 6, 1990, with a return period of 2 years (Reddy, 1989c). The storm lasted for 5.5 hours, producing a total of 66.8 mm of rain. The same storm produced 36.8 mm of rain in Korokula forest, with a maximum intensity of 26.8 mm h^{-1}, and 20.8 mm in Tulasewa forest. This again illustrates the high spatial variation of convective tropical rainfall. This storm also produced the maximum observed 2-hour rainfall intensity of 65.4 mm at Koromani forest.

The number of rain days (defined as a day on which rainfall exceeds 0.2 mm) was highest at Tulasewa forest where rainfall was recorded on 169 days in 1990 and 115 days in 1991 (January – September), and lowest at Korokula forest at 134 and 83 rain days days in 1990 and 1991 (January – September), respectively. The number of rain days at Koromani forest totalled 148 in 1990 and 96 in 1991 (January– September). Rainfall in excess of 0.2 mm was recorded at the latter on 51% of the days during the wet season and on 27% of the days during the dry season. The number of rain storms amounted to 171 in 1990 and 107 in 1991 (January–September) at the Koromani forest plot, where a rainstorm was somewhat arbitrarily defined as a period of rainfall separated from other periods of rainfall by at least four dry hours. The average number of storms per rain day amounted to 1.16 for the wet season and 1.10 for the dry season.

6.4 Rainfall Interception

The amount of rainfall intercepted by a forest, and subsequently lost by evaporation depends on the distribution, surface characteristics and amount of intercepting material (*e.g.* foliage), on the vegetation structure (branching patterns, stocking), on the rainfall duration and intensity as well as on several meteorological variables controlling the evaporation (*e.g.* net radiation, temperature, wind and humidity) (Leonard, 1967).

Under similar climatic conditions, the increase in foliar biomass with forest age should result in an increase in the interception of rainfall, until canopy closure is completed, after which the fraction of rainfall intercepted by the canopy should become fairly constant as the increase in the foliar biomass levels off. A sudden decrease in foliar biomass as a result thinning, cyclone damage, fire, drought, disease or insect attack may result in a temporary decrease in interception loss until the canopy is fully recovered (Rogerson, 1967). This may take from several months to more than a year, depending on the amount of damage inflicted.

The seasonal variation in foliar biomass of pines in Fiji was negligible as these relatively young forests seemed to increase their biomass steadily throughout the rotation period, which excludes this factor as a cause for seasonal variation of interception loss. However, such a variation could be caused by variations in rainfall characteristics (*e.g.* storm size, duration and intensity; Jackson, 1975) or micro-meteorological conditions controlling evaporation (Rowe, 1983). Therefore a distinction was made between wet and dry season interception losses.

Interception and subsequent evaporation of rainfall (E_i) can be calculated from measurements of incident rainfall (P_g), throughfall (Tf) and stemflow (Sf) according to:

$$E_i = P_g - Tf - Sf \tag{6.1}$$

Throughfall amounts were measured at a level of 35 cm above the soil surface, which is well below the maximum height of the undergrowth (1–6 m), and interception losses calculated with Equation 6.1 therefore include those by the undergrowth.

Measured rainfall and throughfall totals for selected periods during the study are summarized in Table 6.4, together with the number of storms (as defined in Section 6.3) in each period, and the resulting mean rainfall amounts. Throughfall amounted to 77% of incident precipitation in both the Tulasewa and Korokula forest plots during the wet season and part of the dry season of 1990 (December/January – July). No throughfall measurements were made in Koromani forest during this period. During the following part of the dry season (July – November) throughfall increased to 84% and 79% of incident rainfall at the Tulasewa and Korokula forest plots respectively. An intermediate value (82% of dry season rainfall) was observed in the Koromani forest plot.

Cyclone Sina afflicted severe damage to Tulasewa forest at the end of November 1990, whereas most trees in the Korokula and Koromani forests were only defoliated. The sudden reduction in foliar biomass caused an increase in throughfall from 77% of incident rainfall during the wet season of 1990 (December/January – July) to 86% and 88% during the wet season of 1991 (December – April) for the Tulasewa and Korokula forest plots respectively. A similar increase may have occurred in Koromani forest where the post-cyclone throughfall amounted to 84% of incident rainfall.

The slightly lower percentage of throughfall in the Tulasewa forest plot, which suffered much higher cyclone damage than Korokula forest, could be caused by the vigorous response of the undergrowth (mainly mission grass) to the opening up of the forest. By the end of the wet season in 1991 the grass had reached heights of 2.5 m. Some rainfall intercepted by the grass presumably reached the forest floor as stemflow rather than as throughfall and post-cyclone amounts of throughfall and stemflow may therefore have been underestimated somewhat. As discussed in Section 5.5 rainfall interception by *Pennisetum polystachyon* grassland may be in the order of 5% of incident rainfall.

The ratio of throughfall to incident precipitation decreased to 78% at the Koromani forest plot, and to 81% at the Tulasewa and Korokula forest plots during the dry season of 1991, which is lower than those observed for the dry season of 1990. This must be due to the difference in rainfall between the dry season of 1990 (420–546 mm) and that of 1991 (150–173 mm; Table 6.4).

Table 6.4: *Observed wet and dry season amounts of rainfall, and observed and predicted amounts of throughfall, stemflow and interception loss for the Tulasewa, Korokula and Koromani forest plots for the pre- and post-cyclone periods. Cyclone Sina occurred on November 28, 1990.*

Period	**P**	**n**	**P-avg**	**Tf**		**Sf**	**Interception loss**					
				Obs.	Pred.	Pred.	Obs.	Pred.	Iwet	Isat	Idry	Istem
	(mm)		(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
Tulasewa Forest												
30/11/89 - 05/01/90	155.6	9	17.3	124.6	126.5	2.0	29.0	27.1	3.0	17.3	6.5	0.3
06/01/90 - 18/07/90	1107.2	98	11.3	849.1	899.1	14.8	243.3	193.2	25.6	123.5	42.0	2.1
19/07/90 - 15/11/90	545.6	50	10.9	459.2	442.2	7.2	79.2	96.2	13.2	60.9	20.8	1.2
16/11/90 - 18/12/90	266.3	18	14.8	220.7	211.1	3.8	41.8	51.5	2.8	45.2	2.9	0.6
19/12/90 - 30/04/91	1378.6	99	13.9	1178.6	1090.6	19.6	180.4	268.3	16.6	230.1	17.5	4.0
01/05/91 - 30/08/91	173.4	30	5.8	141.1	135.9	2.0	30.3	35.6	5.6	25.5	3.8	0.8
30/11/89 - 30/08/91	**3626.7**	**304**	**11.9**	**2973.3**	**2905.3**	**49.4**	**604.0**	**671.9**	**66.8**	**502.5**	**93.5**	**9.0**
Korokula Forest												
08/01/90 - 16/07/90	1047.7	81	12.9	802.9	812.9	14.8	230.0	220.1	30.4	131.7	54.2	3.7
17/07/90 - 19/11/90	422.3	51	8.3	333.6	318.2	5.6	83.1	98.6	20.1	48.0	28.7	1.9
20/11/90 - 24/12/90	246.0	20	12.3	218.1	189.8	3.3	24.6	52.8	4.0	42.4	6.2	0.2
25/12/90 - 29/04/91	761.2	66	11.5	668.0	587.0	10.5	82.7	163.8	12.1	130.0	20.2	1.5
30/04/91 - 02/09/91	150.4	35	4.3	121.2	112.5	1.8	27.4	36.2	7.8	22.7	4.9	0.7
08/01/90 - 02/09/91	**2627.6**	**253**	**10.4**	**2143.8**	**2020.5**	**36.0**	**447.8**	**571.4**	**74.5**	**374.9**	**114.2**	**7.9**
Koromani forest												
08/01/90 - 22/07/90	*1165.1*	*98*	*11.9*	n.d.	*951.1*	*16.3*	n.d.	*197.7*	*26.8*	*114.5*	*51.6*	*4.8*
23/07/90 - 21/11/90	419.7	44	9.5	342.9	335.7	5.5	71.3	78.6	13.2	38.6	24.6	2.2
22/11/90 - 24/12/90	*242.6*	*21*	*11.6*	n.d.	*192.9*	*3.6*	n.d.	*46.1*	*4.0*	*36.2*	*5.4*	*0.5*
25/12/90 - 29/04/91	774.5	79	9.8	650.5	608.7	9.9	114.1	155.9	15.1	109.4	27.8	3.6
30/04/91 - 02/09/91	170.6	33	5.2	132.9	131.3	1.9	35.8	37.5	7.8	21.8	7.1	0.9
23/07/90 - 02/09/91*	**1364.8**	**156**	**8.7**	**1126.3**	**1075.7**	**17.3**	**221.2**	**272.0**	**36.1**	**169.7**	**59.4**	**6.7**

P= Rainfall, n = Number of storms, P-avg = Average rainfall during n storms, Tf = Throughfall, Sf = Stemflow.
Obs.= Field observations, Pred.= Predicted by the Gash model, n.d.= Not determined.
Iwet, Isat, Idry = Interception loss during wetting up, saturation and drying of canopy respectively (Gash model).
Istem = Interception loss from the drying of the trunks (predicted by the Gash model).
*: Values in italics have not been included in totals and averages.

As stemflow was considered to be a small component of the water balance (generally only a few % of P_g in tropical pine forests; Bruijnzeel, 1988) no attempts were made to measure stemflow in the Korokula and Koromani forest plots. Reliable estimates were obtained in the Tulasewa forest plot for small storms only ($P_g < 16$ mm) due to overflow of one or more stemflow collectors during larger storms. The between-tree variation of stemflow was very high with maximum amounts up to 40 times the minimum amount collected during a storm. No stemflow was observed for storms smaller than 3 mm. Gash's analytical model (Gash, 1979), which will be described in Section 6.4.1, was used to predict the stemflow amounts given in Table 6.4. The predicted stemflow amounted to 1.4% of incident rainfall which is in accordance with values found for other tropical pine forests (Bruijnzeel, 1988).

The interception losses (E_i) calculated from Equation 6.1 for the various periods are given in Table 6.4. Pre-cyclone interception losses in the Tulasewa and Korokula forest plots during the wet season of 1990 (December/January – July), expressed as a fraction of P_g, were similar at 22% (Table 6.7). Relative losses decreased in the dry season of 1990 (July – November), although mean rainfall amounts were similar to those in the wet season, and ranged from 14.5% in Tulasewa forest to 19.7% in Korokula forest (Table 6.7). This probably reflects seasonal variations in climate (*e.g.* net radiation, temperature), resulting in lower evaporation rates.

The damage afflicted to the forests by cyclone Sina reduced the interception loss by some 40–50% during the early months season of 1991 as compared to that during the wet season of 1990, with E_i ranging from 10.9% of P_g in the Korokula forest plot to 14.7% in the Koromani forest plot (Table 6.7). Dry season values of E_i, expressed as a fraction of P_g, were slightly lower (18.2% in the Korokula forest plot) or higher (18% and 21% in the Tulasewa and Koromani forest plots, respectively) than those obtained for the dry season of 1990.

Interception losses over the whole period (Table 6.4) did not differ much between the sites, ranging from 16.2% to 17.0% of P_g for the Koromani and Korokula forest plots, respectively, with an intermediate value of 16.7 % for the Tulasewa forest plot. Hence the interception characteristics of these forests seem to be fairly constant after age 6, implying that the largest changes occur during the early years of the plantation.

6.4.1 Modelling of Throughfall, Stemflow and Interception Losses

An analytical model, of which the derivation has been given in detail by Gash (1979), was used to obtain daily estimates of E_i, Tf and Sf from daily rainfall totals. The Gash model has been developed as an attempt to combine the simple features of the empirical regression approach (Helvey and Patrick, 1965; Jackson, 1975; Leonard, 1967; Zinke, 1967) with the conceptual basis of the Rutter model (Rutter *et al.*, 1971, 1975) and has been tested on coniferous and broadleaf forests in temperate climates (Gash, 1979; Gash *et al.* 1980; Pearce and Rowe, 1981; Rowe, 1983) and in tropical climates (Bruijnzeel and Wiersum, 1987; Lloyd *et al.*, 1988; Hutjes *et al.* 1990) with fairly good agreement between observed and predicted interception losses over a large range of precipitation totals (600–2800 mm).

The model is based on the assumption that the actual rainfall pattern can be represented by a series of discrete (*e.g.* daily) storms, separated by periods during which the canopy dries completely. This is a reasonable assumption for SW Viti Levu where rain typically falls in short, intense convective storms, as indicated by the averages (1.1–1.2) for the number of storms on a rain day given in Section 6.3 for Koromani forest. A running water balance is calculated for the canopy and trunks using daily values of incident rainfall as input. The incident rainfall is apportioned into the fraction of rainfall reaching the forest floor without hitting the canopy (free throughfall, p) and the fraction of rainfall diverted to the tree trunks (p_t), with the remaining fraction of P_g assigned to the canopy $(1-p-p_t)$. Gash (1979) assumed that no drip occurred from the canopy until the canopy storage (S) was completely filled, implying that the interception loss from the canopy (E_i) equals $P_g(1-p-p_t)$ if rainfall amounts are insufficient to fill the canopy storage. The amount of rain necessary to fill the canopy storage (P_g') is calculated from Equation 6.2 (Gash, 1979):

$$P_g' = (-\bar{R}S/\bar{E})\ln 1 - (\bar{E}/\bar{R})(1-p-p_t)^{-1}) \qquad (6.2)$$

For storms larger than P_g' the interception loss is the sum of the losses during the period of wetting up (I_{wet}), the period of saturation (I_{sat}) and the period of drying up of the canopy (I_{dry}) as shown in Equation 6.3:

$$E_i = \underbrace{P_g'(1-p-p_t) - S}_{I_{wet}} + \underbrace{\bar{E}/\bar{R}(P_g - P_g')}_{I_{sat}} + \underbrace{S}_{I_{dry}} \qquad (6.3)$$

Gash (1980) further assumed that evaporation from the trunks occurred after rainfall had ceased, which is valid if rainfall durations are short and stemflow fractions low. As such the interception loss from the trunks (E_{it}) is equal to the trunk storage (S_t) for a storm filling the trunk storage completely or to $p_t * P_g$ if rainfall is insufficient to fill the trunk storage.

The evaporation rate from the saturated canopy during rainfall is assumed to be constant and equal to the average rate ($\bar{E}$) for all storms. Gash (1979) has shown that the slope (a) in a linear regression equation ($E_i = a \cdot P_g + b$) of observed interception losses (E_i) on P_g is given by the ratio of $\bar{E}$ to $\bar{R}$, where $\bar{R}$ is the mean rainfall rate onto a saturated canopy. $\bar{E}$ can be determined from the slope (a) of the regression when $\bar{R}$ is known, or alternatively from above-canopy micro-meteorological data using the Penman-Monteith equation with r_s set to zero (Gash, 1979; Gash *et al.* 1980).

The free throughfall coefficient was determined from the coefficient of a regression of Tf on P_g for small storms insufficient to saturate the canopy (Gash and Morton, 1978). Single storm rainfall and throughfall data with rainfall amounts of less than 2.7 mm were used to determine p for the pre- and post-cyclone periods. The pre-cyclone free throughfall coefficients ranged from 0.54 (n= 6) and 0.56 (n= 4) for Korokula and Koromani forests respectively, to 0.60 (n= 6) for Tulasewa forest (Figure 6.1A), where n represents the number of storms used in the regression. The regression equations used for the derivation of the various Gash model parameters for each of the forests are given in Table 6.5. The post-cyclone values of p were even higher ranging from 0.58 (n= 3) for the Korokula forest plot to 0.69 (n= 6) and 0.71 (n= 6) for the Koromani and Tulasewa forest plots, respectively. However, due to the limited number of single storms used in the regressions the errors in p may be considerable.

Shuttleworth (1989) found average values of about 0.1 for p in a comparison of interception studies in temperate and tropical forests. In Java, Bruinzeel and Wiersum (1987) obtained estimates of 0.34–0.38 in a 4–5-year-old *Acacia auriculiformis* plantation, whereas Bons (pers. comm.) obtained a value of 0.26 for p for a 35-year-old *Pinus merkusii* plantation forest. The relatively high values of p found in the present study are consistent with the rather open character of the pine forests in Fiji and were

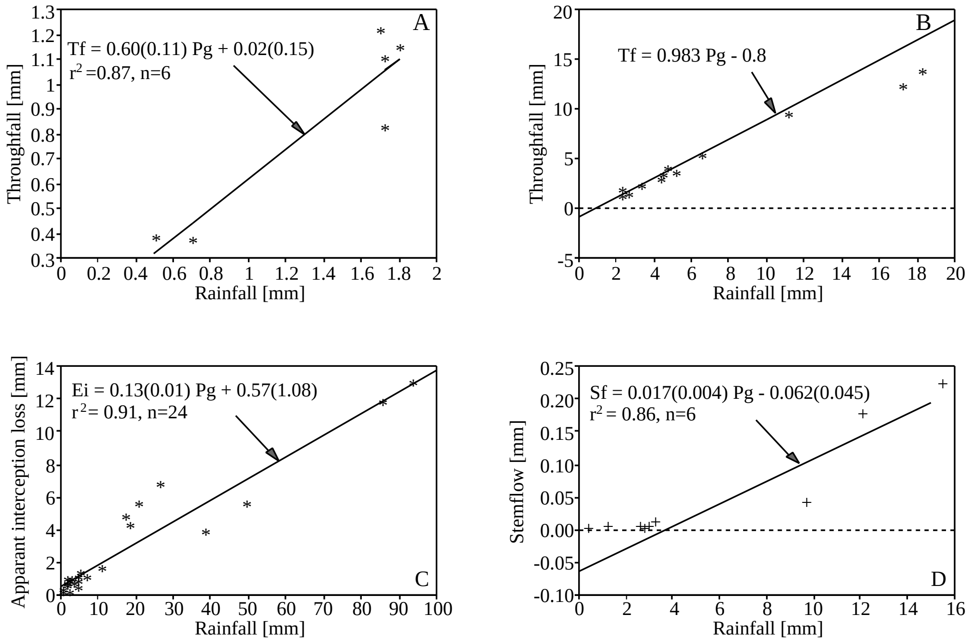


Figure 6.1: *Determination of pre-cyclone free throughfall coefficient (A), canopy storage capacity (B) $\bar{E}/\bar{R}$ (C) as well as stemflow fraction and trunk storage capacity (D) for the Tulasewa forest plot.*

Table 6.5: *Regression coefficients and statistics of linear regressions ($Y = a \cdot X + b$) of throughfall (Tf), interception loss (E_i) and stemflow (Sf) on incident rainfall (P_g) for the Tulasewa, Korokula and Koromani forest plots.*

Location	Equation	r^2	n	Storm size
Tulasewa				
Pre-cyclone	$Tf = 0.604(0.116)P_g + 0.015(0.153)$	0.87	6	< 2.7 mm
	$E_i = 0.132(0.008)P_g + 0.571(1.083)$	0.91	24	all storms
Post-cyclone	$Tf = 0.714(0.108)P_g + 0.048(0.100)$	0.92	6	< 2.7 mm
	$E_i = 0.183(0.051)P_g - 0.020(0.794)$	0.68	8	all storms
Whole period	$Sf = 0.017(0.004)P_g - 0.062(0.045)$	0.86	5	< 16.0 mm
Korokula				
Pre-cyclone	$Tf = 0.539(0.074)P_g + 0.235(0.109)$	0.93	6	< 2.7 mm
	$E_i = 0.154(0.044)P_g + 0.408(0.639)$	0.58	11	all storms
Post-cyclone	$Tf = 0.581(0.082)P_g + 0.390(0.079)$	0.98	3	< 2.7 mm
	$E_i = 0.194(0.040)P_g - 0.269(1.226)$	0.86	6	all storms
Koromani				
Pre-cyclone	$Tf = 0.556(0.115)P_g + 0.047(0.125)$	0.92	4	< 2.7 mm
	$E_i = 0.117(0.017)P_g + 0.826(1.643)$	0.79	14	all storms
Post-cyclone	$Tf = 0.685(0.097)P_g - 0.052(0.238)$	0.93	6	< 2.7 mm
	$E_i = 0.166(0.004)P_g - 0.307(0.355)$	0.99	12	all storms

confirmed by canopy gap fraction measurements using a ceptometer, as well as by measurements of projected crown area in the Koromani forest plot (Opdam, 1993). In the Tulasewa forest plot the pre-cyclone canopy gap fraction, as measured in June 1990, was 0.47(±0.14) which had increased slightly, but not significantly, to 0.50(±0.26) by July 1991. Post-cyclone gap fractions in the Korokula and Koromani forest plots were 0.28(±0.23) and 0.46(±0.26), respectively. The gap fractions were measured at 1.3 m, which is just below the upper levels of the undergrowth, and slightly lower values may be expected at the level where throughfall was collected (0.4 m).

The canopy storage capacity (S) was determined by the method of Leyton *et al.* (1967) using data for single storms larger then 2.7 mm. A straight line with a slope of $(1 - p_t)$ was drawn through the points such that the line passed through those points representing conditions with minimum evaporation (*e.g.* Figure 6.1B). S was then given by the intercept of that line with the throughfall axis. Pre-cyclone values of S were 0.8 mm (n= 18), 1.4 mm (n= 5) and 1.2 mm (n= 10) found in the Tulasewa, Korokula and Koromani forest plots, respectively (Table 6.6). Post-cyclone values of S were lower, reflecting the loss of foliage, amounting to 0.3 mm (n= 6), 0.5 mm (n= 3) and 0.6 mm (n= 6), respectively. Typical values of S for lowland tropical rainforest are 0.8–0.9 mm (Jackson, 1975; Lloyd *et al.*, 1988) whereas values similar to the presently found pre-cyclone figures have been reported for 4—5-year-old *Acacia auriculiformis* (S= 0.5–0.6 mm; Bruijnzeel and Wiersum, 1987) and 35-year-old *Pinus merkusii* plantations (S= 0.6–1.0; Mr. C.A. Bons, pers. comm.) in Java.

$\bar{E}/\bar{R}$ values for the pre- and post-cyclone periods were calculated from the slopes of regressions of interception loss E_i (approximated by $P_g - Tf$), on P_g for all single storms (*e.g.* Figure 6.1C). The pre-cyclone values were 0.132 (n= 24), 0.154 (n= 11) and 0.117 (n= 14) for the Tulasewa, Korokula and Koromani forest plots, respectively

Table 6.6: *Vegetation parameters and adjusted $\bar{E}/\bar{R}$ values used in the Gash model to predict daily throughfall and stemflow.*

Period	S	p	S_t	p_t	$\bar{E}/\bar{R}$	$\bar{E}/\bar{R}$ adjusted
Tulasewa						
Pre-cyclone	0.8	0.60	0.062	0.017	0.132	0.147
Post-cyclone	0.3	0.71	0.062	0.017	0.184	0.125
Korokula						
Pre-cyclone	1.4	0.54	0.062	0.017	0.154	0.160
Post-cyclone	0.5	0.58	0.062	0.017	0.193	0.087
Koromani						
Pre-cyclone	1.2	0.56	0.062	0.017	0.117	0.123
Post-cyclone	0.6	0.61	0.062	0.017	0.166	0.114

(Tables 6.5 and 6.6). The low value of $\bar{E}/\bar{R}$ for the Koromani forest plot compared to that for the Korokula forest plot may be caused by the lack of wet season measurements for the former, during which evaporation rates were presumably higher as a result of higher temperatures and radiation. Post-cyclone $\bar{E}/\bar{R}$ values were higher at 0.183 (n= 8), 0.194 (n= 6) and 0.166 (n= 12) for the Tulasewa, Korokula and Koromani forest plots, respectively. As one would expect a lower $\bar{E}$ after defoliation whereas large changes in $\bar{R}$ were not observed as shown below, this is believed to reflect the limited number of single storms (particularly larger storms) sampled during this fairly dry period, rather then an actual increase in $\bar{E}/\bar{R}$. Bruijnzeel and Wiersum (1987) and Bons (pers. comm.) obtained respective values of 0.07–0.14 and 0.20–0.22 for $\bar{E}/\bar{R}$ in their forests discussed earlier in this section.

The average rainfall rate onto a saturated canopy was calculated from half-hourly pre-cyclone rainfall totals and amounted to 5.5 mm h^{-1} at Tulasewa forest in 1990, with a dry season average of 5.0 mm h^{-1}. This would result in apparent pre-cyclone $\bar{E}$ values of 0.72 mm h^{-1}, 0.85 mm h^{-1} and 0.59 mm h^{-1} for the Tulasewa, Korokula and Koromani forest plots, respectively. A post-cyclone value for $\bar{R}$ of 4.7 mm h^{-1} was obtained from data collected at Koromani forest, resulting in post-cyclone $\bar{E}$ values of 0.86 mm h^{-1}, 0.91 mm^{-1} and 0.78 mm h^{-1} for the Tulasewa, Korokula and Koromani forest plots, respectively. These values are much higher than the ones calculated on the basis of above canopy weather data (Section 7.7, Table 7.6). Possible reasons for this discrepancy are given later in this section.

The trunk storage capacity (S_t) and the fraction of rainfall going to the trunks were determined from the regression of stemflow (Sf) on incident rainfall (Gash and Morton, 1978) as measured in the Tulasewa forest plot (Figure 6.1D, Table 6.5). This suggested values for S_t and p_t of 0.062 and 0.017, respectively, and these were used to calculate the stemflow component for Tulasewa forest, as well as for Korokula and Koromani forests (Table 6.6). These values compare rather well to those obtained by Bons (pers. comm.) from measurements of stemflow in a 35-year-old *Pinus merkusii* plantation in Java (S_t= 0.026 and p_t= 0.028). The pre- and post-cyclone values of S,

p, S_t, p_t and $\bar{E}/\bar{R}$ found for the various sites have been summarized in Table 6.6.

The Gash model was run on daily rainfall data using the appropriate model parameters for each period. The observed and the predicted throughfall and stemflow amounts and interception losses are compared in Table 6.4. Predicted throughfall amounts were only 2% (Tulasewa forest plot) to 6% (Korokula forest plot) lower than the observed totals over the whole period. This resulted in an overestimation of interception losses, ranging from 11% at the Tulasewa forest plot to 28% at the Korokula forest plot, whereas that at the Koromani forest plot was overestimated by 23%.

The predicted throughfall amounts for the pre-cyclone period on the other hand were very close to the observed values with absolute deviations of less than 2.5% from observed amounts for all forests. Predicted interception losses were therefore much closer to observed losses for this period with absolute deviations of less than 11% from the observed values. These deviations are similar to those obtained by Bruijnzeel and Wiersum (1987) in an Indonesian *Acacia auriculiformis* plantation and smaller than those found in applications of the model in tropical rain forests (−35%, Hutjes *et al.*, 1990; +27%, Lloyd *et al.*, 1988) .

Much larger deviations from observed throughfall amounts were found for the post-cyclone period, ranging from -5.5% for Koromani forest to -11.7% for Korokula forest. As such interception losses were overestimated, with deviations ranging from +29% in the Koromani forest plot, to +88% in the Korukola forest plot. This is not very surprising as the post-cyclone model parameters were based on only very few single storms which, in addition, were collected in a period when the canopy was not in a steady state due to rapidly regenerating foliage. The obtained post-cyclone values for S and p nevertheless seemed reasonable considering the damage afflicted to the forests. However, the much larger post-cyclone values of $\bar{E}/\bar{R}$ compared to the pre-cyclone values (0.117–0.154) seem unrealistic as meteorological conditions were broadly similar during both periods.

Alternatively, evaporation rates during rainfall may be calculated from above canopy micro-meteorological data using the Penman-Monteith formula (Monteith, 1965, Equation 5.3) with r_s set to zero for the time that the canopy is wet (Section 7.7, Table 7.6). The $\bar{E}/\bar{R}$ values obtained with the Penman-Monteith method were several times smaller than those obtained from the above mentioned regression analysis on rainfall and throughfall data. There may be several explanations for these discrepancies. The estimates obtained with the Penman-Monteith equation are likely to be underestimated as advective energy inputs were not taken into account (Stewart, 1977). Sources of advective energy can easily be identified in the study area, where the forests were close to the Pacific Ocean and surrounded by grassland. The mean daily temperature of days with rainfall exceeding 10 mm was 24.2(±1.8) °C, whereas the mean sea surface temperature varied between 25 °C and 28 °C (Basher, 1986b). Therefore a horizontal temperature gradient followed by a downward sensible heat flux (Pearce *et al.*, 1980) is likely to exist when the temperature over land drops below that of the seawater (*e.g.* at night, during periods with rainfall). Because r_s for a dry canopy is high during nighttime, such an extra advective energy input will not result in transpiration. However, when the canopy is wet the extra energy input may be used for evaporation of moisture from the canopy, and the rates derived with the Penman-Monteith equation may therefore be considered underestimates under such conditions.

The lack of stemflow data for large storms may also have resulted in errors in the estimated $\bar{E}/\bar{R}$ values obtained from regressions of E_i on P_g, because the interception loss was approximated by $P_g - Tf$, neglecting the contribution of stemflow.

This approximation may be valid for small storms, during which the branches and stems are not thoroughly wetted. However, the structure of the tree crowns was such (Section 11.3) that the proportion of rainfall going to the trunks may have become much higher when branches and stems were saturated, as large amounts of water intercepted by needles and branches pointing upwards at angles of more than 45° may have been conducted towards the trunk. Interception losses for large storms may have been overestimated, therefore resulting in the obtained high $\bar{E}/\bar{R}$ values.

6.4.2 Modelling Moisture Fluxes through the Litter Layer

Accurate estimates of the amounts of water percolating through the litter and fermentation layers could not be obtained for storms exceeding 25–30 mm due to overflow of the collectors. A simple model was developed therefore to obtain daily estimates of litter percolate volumes (D_{lf}) and rainfall interception by the litter layer (E_{il}) using daily throughfall and stemflow amounts as predicted by the Gash model as input. A description of the model and the assumptions made during its derivation are given below.

Interception of rainfall by the litter layer is a function of the micro-meteorological conditions within the forest, as well as the moisture content (MC_l), and thus the storage capacity (S_l) of the litter layer. Amounts of radiation reaching the forest floor depend on the areal distribution of pine foliage and undergrowth. Fractions of photosynthetically active radiation (PAR) reaching the undergrowth level (1.3 m) ranged from 21% of incoming PAR in the Korokula forest plot to 36% and 39% in the Koromani and Tulasewa forest plots, respectively (see Section 11.3.6). Tannai and Hattori (1993) observed that the influence of $R_s\downarrow$ on evaporation from the forest floor (E_l) was small during the growing season of a deciduous broad-leaved forest in Japan and that E_l was basically constant under the prevailing climatic conditions. Because below canopy wind speeds in the forests in Fiji are low it is safe to assume that the evaporative demand at the forest floor will not be high and that temporal variations in micro-meteorological conditions just above the forest floor will be relatively small. As such the moisture status of the litter layer may be identified as the main factor determining E_l.

A general relationship between the moisture content of the litter layer, obtained from samples collected at regular time intervals during the study (see Section 11.2), and the time passed since the last rainfall event (t) is shown in Figure 6.2. The moisture content of each sample was corrected for differences in litter mass at the time of sampling by normalizing it to that of the average pre-cyclone mass. There were no significant differences between the forest sites, despite differences in the mass and composition of the litter layer. Therefore a single exponential curve was fitted through the combined data set. Litter samples which contained less than 1.5 mm of water within 20 hours or less than 1 mm within 80 hours after sampling were excluded as the amount of rainfall may not have been sufficient to saturate the litter layer completely. When t exceeded 200 hours the moisture content remained essentially constant at 0.2–0.3 mm. The decrease in moisture content (MC) as a function of time t could be described accurately by Equations 6.4 and 6.5.

$$0 \leq t \leq 200: \; MC_l = 2.43\exp^{-0.0135t}$$
$$\text{n}= 18,\; r^2 = 0.94 \tag{6.4}$$

$$t > 200: \; MC_l = 0.2 \tag{6.5}$$

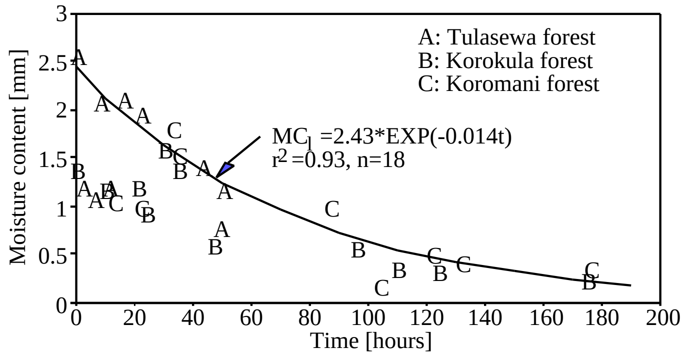


Figure 6.2: *Relationship between litter layer moisture contents and time since the last rainfall event for the three study plots.*

The maximum pre-cyclone moisture content of the litter layer (MC_{lmax}) was assumed to be equal to the moisture content at time t= 0 and amounted to 2.4 mm (Equation 6.4). Therefore moisture storage (S_l) was allowed to vary between 0.0 (air dry) and 2.2 mm (saturated, S_{lmax}). The pre-cyclone maximum was multiplied by the average ratio of the post- to pre-cyclone mass (1.67) which gave a value of 4.0 mm for the maximum post-cyclone moisture content.

For any MC_l value a corresponding t value could be calculated using an exponential regression equation (Equation 6.6) of t on $MC_l(t)$.

$$t = 220.9 \exp^{-1.251MC_l}$$
$$\text{n}= 18,\ r^2 = 0.93 \tag{6.6}$$

The rate of removal of moisture from the litter layer by evaporation (E_l) is described by Equations 6.7 and 6.8, which represent the first order derivatives of Equations 6.4 and 6.5.

$$0 \le t \le 200: \ E_l = 0.034 \exp^{-0.0135t} \tag{6.7}$$

$$t > 200: \ E_l = 0 \tag{6.8}$$

Equation 6.7 implies an evaporation rate of 0.034 mm h^{-1} at t= 0 or 0.79 mm day^{-1}, for a saturated litter layer (E_{lsat}). The actual evaporation from the litter layer during rainfall may have been even higher as additional energy for evaporation may have been provided by cooling of the air within the forest.

Stemflow was assumed to reach the soil without interception by the litter layer, as the flow is concentrated in a small area around the trunk of the tree. Depending on the amount of throughfall the model selected one out of four possible options to calculate the interception by the litter layer (E_{il} and the flux of water through the litter layer (D_{lf}):

1. If Tf= 0 the moisture content of the litter layer decreases from $MC_l(t)$ to $MC_l(t + 24)$ according to Equation 6.4. Both E_{il} and D_{lf} are zero.
2. For $0 < Tf < S_l(t)$ all throughfall is used to increase the MC_l and a corresponding t_{new} is calculated from Equation 6.6. MC_l then becomes $MC_l(t_{new} + 24)$; E_{il} equals Tf and D_{lf} is zero.

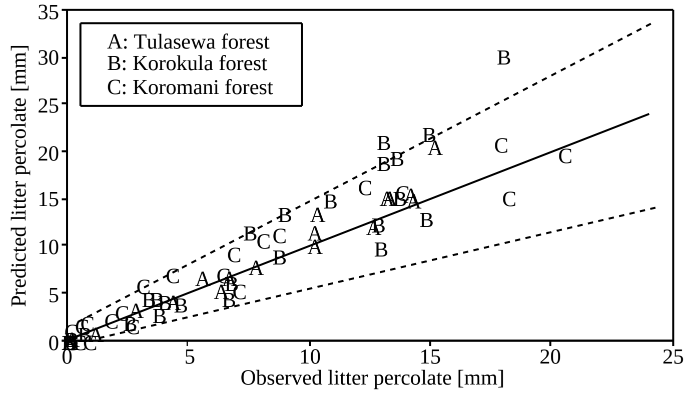


Figure 6.3: *Observed and predicted moisture fluxes through the litter layers of Tulasewa, Korokula and Koromani forests. The solid line is a line of unit slope whereas the dotted lines represent the range of standard deviations of the observed fluxes.*

3. For $S_l(t) < Tf < S_{lmax} + E_{lsat}$, MC_l is set to MC_{lmax} and t is set to zero. E_{il} equals Tf and D_{lf} is zero.
4. For $Tf > S_{lmax} + E_{lsat}$, MC_l is set to MC_{lmax}, t is set to zero, E_{il} is set to $S_{lmax} - S_l(t) + E_{lsat}$ and D_{lf} equals $Tf - E_{il}$.

As indicated earlier, the Gash model was used to obtain daily values of throughfall and stemflow to be used as inputs to the litter layer interception model. The $\bar{E}/\bar{R}$ values to be used were adjusted by trial and error until the predicted throughfall totals were equal to the observed totals given in Table 6.4. The vegetation parameters and the adjusted $\bar{E}/\bar{R}$ values are shown in Table 6.6. The empirical $\bar{E}/\bar{R}$ values were similar to the adjusted ones for the pre-cyclone period, whereas the adjusted post-cyclone values were much lower than the empirical ones, and approached pre-cyclone values (with the exception of that of the Korokula forest plot, Table 6.6).

To test the model a comparison was made between observed and predicted amounts of litter percolate for daily rainfall totals smaller than 20 mm (Figure 6.3). The model seems to overestimate the moisture fluxes through the litter layer because the sum of the predicted totals was 9% (Tulasewa forest) to 21% (Korokula forest) higher than the sum of the observed totals. However, no corrections were made as the predicted values were generally within the range of the standard deviations of the measured volumes.

Predicted fluxes of moisture through the litter layer for various periods during the study are given in Table 6.7 together with observed rainfall and throughfall amounts, and predicted stemflow amounts. The interception loss from the litter layer was calculated from Equation 6.9 and ranged from 9.5% of total rainfall in Tulasewa forest to 11.0% in Korokula forest.

$$E_{il} = (Tf + Sf) - D_{lf} \tag{6.9}$$

As shown in Table 6.7 interception losses from the litter layer were relatively low during the wet season (4–10% of rainfall) as the time between consecutive rainfall events was

Table 6.7: *Observed amounts of rainfall and throughfall, and predicted amounts of stemflow and litter percolate for Tulasewa, Korokula and Koromani forests. Interception losses from the canopy and litter layer are expressed both as depths of water and as a percentage of total rainfall.*

Period	**Rainfall**	**Throughfall**	**Stemflow**	**Litter Percolate**	**Interception loss**			
					Canopy		**Litter layer**	
	(mm)	(mm)	(mm)	(mm)	(mm)	% Rainfall	(mm)	% Rainfall
Tulasewa Forest								
30/11/89 - 05/01/90	155.6	124.6	*2.0*	*106.7*	29.0	18.6	19.9	12.8
06/01/90 - 18/07/90	1107.2	849.1	*14.8*	*789.6*	243.3	22.0	74.3	6.7
19/07/90 - 15/11/90	545.6	459.2	*7.2*	*388.1*	79.2	14.5	78.3	14.4
16/11/90 - 18/12/90	266.3	220.7	*3.8*	*214.5*	41.8	15.7	10.0	3.8
19/12/90 - 30/04/91	1378.6	1178.6	*19.6*	*1064.0*	180.4	13.1	134.2	9.7
01/05/91 - 30/08/91	173.4	141.1	*2.0*	*115.1*	30.3	17.5	28.0	16.1
30/11/89 - 30/08/91	**3626.7**	**2973.3**	**49.4**	**2678.0**	**604.0**	**16.7**	**344.7**	**9.5**
Korokula Forest								
08/01/90 - 16/07/90	1047.7	802.9	*14.8*	*735.1*	230.0	22.0	82.6	7.9
17/07/90 - 19/11/90	422.3	333.6	*5.6*	*276.2*	83.1	19.7	63.0	14.9
20/11/90 - 24/12/90	246.0	218.1	*3.3*	*184.5*	24.6	10.0	36.9	15.0
25/12/90 - 29/04/91	761.2	668.0	*10.5*	*598.5*	82.7	10.9	80.0	10.5
30/04/91 - 02/09/91	150.4	121.2	*1.8*	*97.7*	27.4	18.2	25.3	16.8
08/01/90 - 02/09/91	**2627.6**	**2143.8**	**36.0**	**1892.0**	**447.8**	**17.0**	**287.8**	**11.0**
Koromani forest								
08/01/90 - 22/07/90	1165.1	*945.2*	*16.3*	*867.0*	203.6	17.5	94.5	8.1
23/07/90 - 21/11/90	419.7	342.9	*5.5*	*294.7*	71.3	17.0	53.7	12.8
22/11/90 - 24/12/90	242.6	*204.7*	*3.6*	*185.1*	34.3	14.1	23.2	9.6
25/12/90 - 29/04/91	774.5	650.5	*9.9*	*560.4*	114.1	14.7	100.0	12.9
30/04/91 - 02/09/91	170.6	132.9	*1.9*	*103.5*	35.8	21.0	31.3	18.3
23/07/90 - 02/09/91	**2772.5**	**2276.2**	**37.2**	**2010.7**	**459.1**	**16.6**	**302.7**	**10.9**

Values predicted by the Gash and litter layer interception models shown in italics too short to deplete the storage of moisture completely. Dry season interception losses from the litter layer were relatively high and comparable to those in the canopy, ranging from 13–18% of total rainfall. The combined interception losses from the canopy and litter layer ranged from 26% of total rainfall for Tulasewa forest to 28% for Korokula forest. This would imply a total interception loss of 444–475 mm for a year with average rainfall (Table 6.2).

An overview of estimates of E_i including some obtained in coniferous plantation forests in the humid tropics has been presented by Bruijnzeel (1988). E_i was found to vary between 7% of rainfall for a 4–6 year old *Pinus caribaea* forest in Brazil (Shuttleworth, 1988) and 23% for a *Pinus merkusii* plantation forest in West Java (Bruijnzeel, 1988), whereas a value of 17% was found for an 18-year-old *Pinus caribaea* forest in Jamaica (Richardson, 1982). Interception losses from the litter layer are usually neglected in rainfall interception studies, and we have not been able to find any information for comparison with the values presently obtained.

6.5 Forest Evapotranspiration as derived from Soil Moisture Depletion

Soil moisture profiles (θ) were determined regularly throughout the dry season of 1990 and 1991 using a capacitance probe (*cf.* Appendix 24). The average depths of the θ profiles sampled were 1.0 m, 0.6 m and 0.8 m in the Tulasewa, Korokula and Koromani forest plots, respectively. Although the largest concentration of roots was observed in the upper 0.5 m of the soil, roots were also observed penetrating the bedrock at depths between 0.8 and 1.6 m. Because the pine root network extended beyond the maximum depth of the access tubes, and therefore of the moisture measurements, the zero flux plane approach (Cooper, 1979; *cf.* Section 5.2) could not be used to distinguish between moisture removed by evapotranspiration (ET_{sm}) and by drainage. The importance of drainage (D in mm day^{-1}) during periods without rainfall was therefore evaluated from the Darcy equation for unsaturated flow (Equation 6.10), assuming stationary flow conditions and using modelled values of K_{unsat} (or K_θ, see Appendix 25 and Section 4.3.4) in combination with pressure gradients ($\frac{\partial H}{\partial z}$) as obtained from tensiometer readings at various depths in the soil (Hanks and Ashcroft, 1980).

$$D = -K_{unsat} \cdot \frac{\partial H}{\partial z} \tag{6.10}$$

Variations with time of the soil moisture tension (with reference to the soil surface) for two depths in the soil at each of the forest sites are shown in Figure 6.4. The pressure gradients were usually low ranging from -7 to 15 cm H_2O cm^{-1} during dry periods. The modelled unsaturated hydaulic conductivities were low as well for tension values drier than field capacity (pF= 2.0; Appendix 25). Hence the contribution of drainage to the removal of moisture from the soil could safely be neglected after 3–5 days since a major rainfall event during the dry season.

The loss of moisture during such rainless periods without drainage were therefore nevertheless (even though it is recognised that the results must represent underestimates due to the fact that some roots extended beyond the depth of moisture observations) calculated from consecutive measurements of θ profiles. Time series of θ measured at several depths in access tubes A1, B1 and C1 (for which the longest records were available) in the respective forest plots are shown in Figure 6.5. The soil

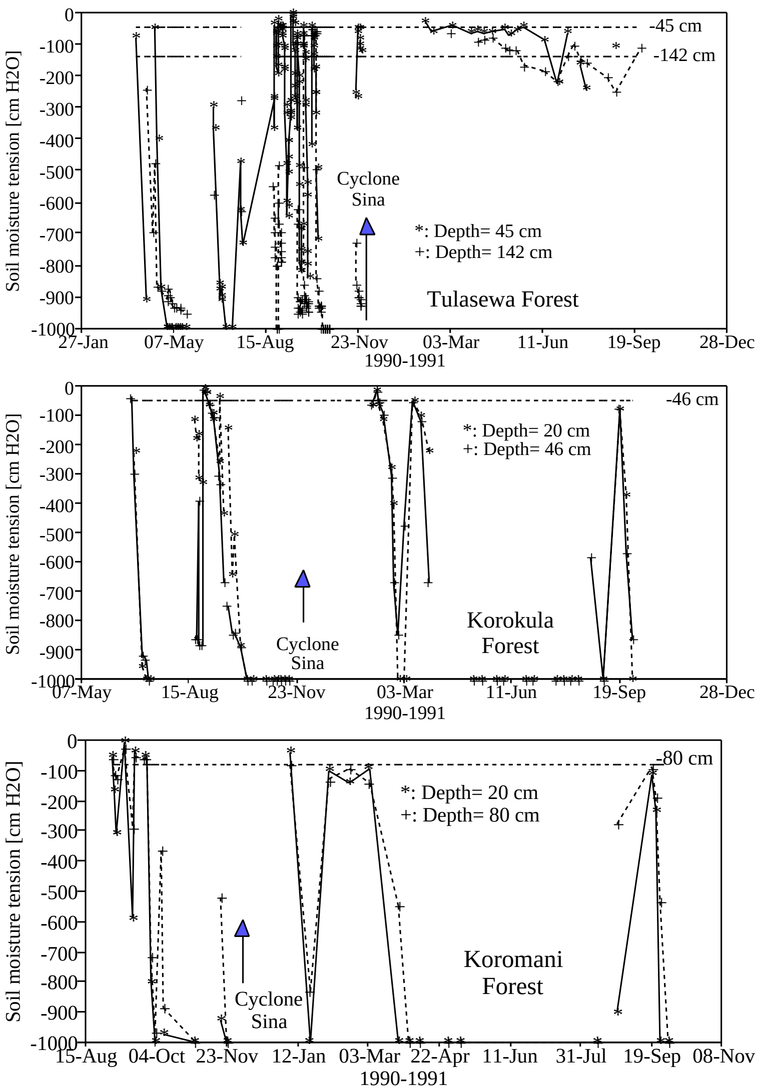
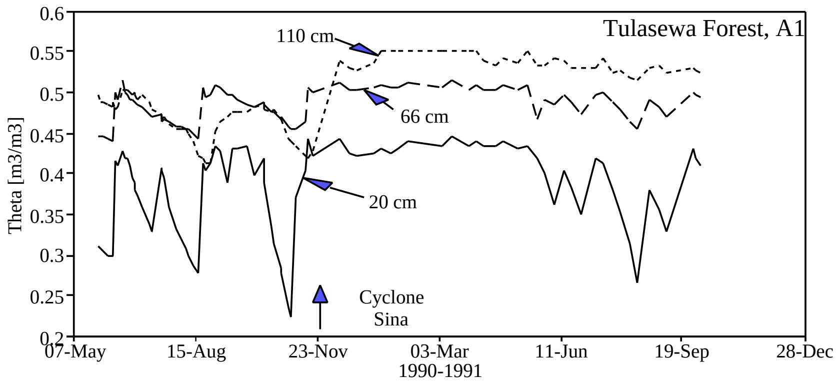
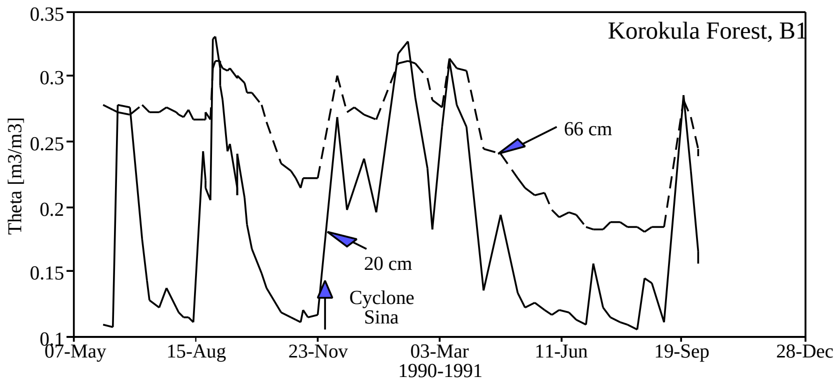


Figure 6.4: *Time series of soil moisture tension at two depths in the Tulasewa, Korokula and Koromani forest plots. Dry periods during which the soil moisture tension was higher than -1000 cm H_2O are indicated by the respective labels on the X-axis. Saturated conditions occurred whenever values exceeded the dashed lines indicating the depth of the respective observations.*





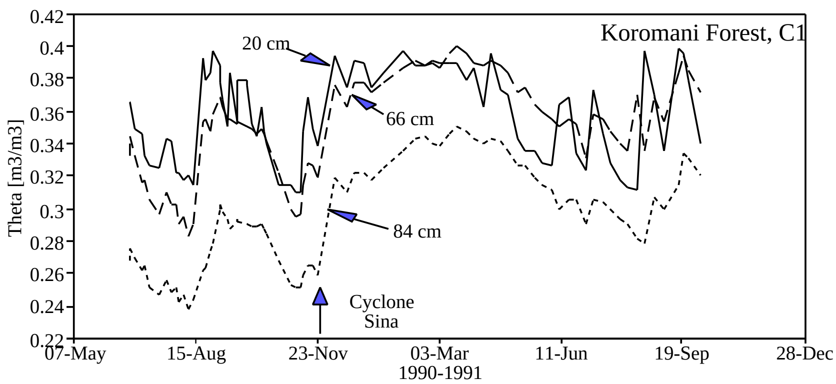


Figure 6.5: *Time series of θ at various depths in the Tulasewa, Korokula and Koromani forest plots as measured in capacitance probe access tubes A1, B1 and C1, respectively.*

Table 6.8: *Average ET_{sm} rates (mm day^{-1}) for Tulasewa, Korokula and Koromani forests during the dry seasons of 1990 and 1991 and interception losses E_i (including interception by the litter layer) observed over the periods for which ET_{sm} was calculated. Total ET (mm day^{-1}) was calculated as the sum of ET_{sm} and the average daily interception loss. The number of days was variable in 1990 depending on the number of access tubes installed at the time.*

Location	Tulasewa forest		Korokula forest		Koromani forest	
Year	1990	1991	1990	1991	1990	1991
ET-sm	3.27	2.23	1.41	0.90	1.81	1.67
Standard deviation	0.61	0.49	0.40	0.20	0.27	0.19
Number of days	86-16	69	85-48	86	98-50	89
Interception loss	23.4	8.4	38.3	8.8	45.5	10.1
Total ET	3.54	2.35	1.86	1.00	2.27	1.78

moisture content showed a clear seasonal trend with large fluctuations of θ, both in the topsoil and in the subsoil, during the dry seasons, and much smaller fluctuations during the wet season when the whole soil profile remained near field capacity. The large fluctuations in the subsoil of the forest plots, in contrast to those observed below the root zone in the Nabou grassland plot (*cf.* Section 5.3), constitute further evidence of water extraction by the pine roots beyond the depths of observations.

Cyclone Sina destroyed 42% of all trees in the Tulasewa forest plot, including those surrounding access tube A1, and defoliated the surviving trees. This was followed by vigourous regrowth of grass during the wet season of 1991. The damage to the forest resulted presumably in lower ET rates during the dry season of 1991 as compared to those in 1990. As a result soil moisture levels in the dry season of 1991 did not drop to the low levels observed during the dry season of 1990, despite lower rainfall inputs during the former (503 mm *versus* 351 mm). This is evident in the time series of the soil moisture tension (Figure 6.4) as well as in those for θ (Figure 6.5). Soil moisture profiles measured in the other access tubes in the Tulasewa forest plot (A2–A5) confirmed the pattern shown for access tube A1 in Figure 6.5.

The damage to the older forests was mainly confined to a reduction of the amount of foliage on the trees as less than 5% of the trees had been destroyed, and regrowth of needles was rapid. This, and the fact that the dry season of 1991 was much drier than that of 1990, may explain why there were no pronounced differences between dry season minimum soil moisture levels in 1990 and 1991. An exception must be made for access tube C1 in the Koromani forest plot, where a tree close to the access tube had been destroyed, and where dry season soil moisture levels in showed a similar trend, although not as pronounced, to those measured in access tube A1 in the Tulasewa forest plot (Figure 6.5). This suggests that cyclone Sina increased the spatial variation in soil moisture considerably in 1991 due to local disturbances to the forest (*e.g.* tree fall).

The average daily ET_{sm} rates for the Tulasewa, Korokula and Koromani forest plots are given in Table 6.8. As the access tubes were installed during the dry season of 1990 the ET_{sm} rates for that season represent the average obtained from a steadily increasing number of tubes. There were large differences between the ET_{sm} rates obtained for the various plots with the highest rates observed in Tulasewa forest and the lowest in Korokula forest. However, as explained earlier, the rates presented in Table 6.8 must be considered underestimates as only the upper part of the soil profile containing roots could be sampled. The results of various micro-meteorological approaches to the evaluation of forest ET will be presented in Chapter 7.

The effect of cyclone Sina on rates of ET_{sm} was evident in Tulasewa forest where a reduction of 32% was observed for the dry season of 1991 compared to that of 1990. This reduction could not have been caused by differences in rainfall between the seasons as moisture was not limiting in 1991 (Figure 6.4). The lower ET_{sm} rates observed in Korokula and Koromani forests (36% and 8% respectively) in 1991 compared to those in 1990 may reflect a combination of reductions in the LAI of these forests (*cf.* Section 11.3.6) and, in the case of Korokula forest, also the relatively low plant available water capacity of the soil (Section 4.3.4).

6.6 Moisture Fluxes through the Soil

As explained in the previous section, amounts of water draining to deep groundwater (D) during the wet season were not measured directly. These were therefore estimated from a simple water balance equation (Ward and Robinson, 1990):

$$Q + D = P - ET \pm \Delta S \tag{6.11}$$

Similarly, ET was not measured continuously at all plots either and several assumptions were therefore needed to obtain estimates of D for both pre- and post-cyclone periods. As a result, the errors in these estimates may be considerable.

Pre-cyclone estimates of ET for the young forest at the Tulasewa forest plot (4.85 mm day^{-1}) were obtained by micro-meteorological techniques (Section 7.7), and at Oleolega for the mature forest (4.3 mm day^{-1}) by means of the catchment water balance method (Chapter 8). Because age and tree density of Koromani forest were roughly similar to those of the Oleolega forest, the pre-cyclone ET of Koromani forest was assumed to equal that of Oleolega forest. For want of actual observations ET at the Korokula forest plot was also assumed to be equal to that of Oleolega forest, in spite of the higher tree density in the former, because occasional water stress during dry periods is likely to have reduced ET to some extent at the Korokula forest plot (*cf.* Table 6.8). Pre-cyclone rainfall inputs, estimated ET totals and derived amounts of D are presented in Table 6.9. The runoff coefficients (D/P) calculated for the Tulasewa and Korokula forest plots were lower, whereas that for the Koromani forest plot was slightly higher than that calculated for the Oleolega catchment (0.16, Chapter 8). The relatively low values calculated for the former plots seem reasonable in view of the higher tree density in these sites compared to the other sites (Chapter 3).

Post-cyclone measurements of forest ET were limited to Koromani forest during the dry season of 1991. Because the wet season rainfall totals at the Korokula (831 mm) and Koromani forest plots (835 mm) were quite similar to that at Oleolega forest (904 mm), drainage losses during the 1990/1991 wet season and for September, 1991 (a wet month; Table 6.2), were approximated using the wet season runoff coefficient obtained for the Oleolega catchment (0.23; Chapter 8). The 1991 dry season rainfall was low and the soils at the Korokula and Koromani forest plots were relatively dry from April until September (Figures 6.4 and6.5) and drainage during this period may safely be neglected. The overall post-cyclone estimates of drainage rates for the two forest plots are presented in Table 6.9. The apparent post-cyclone ET value obtained

Table 6.9: *Components of the water balance for the pre- and post-cyclone periods at Tulasewa, Korokula and Koromani forests, n is the number of days in each period. Note that the pre-cyclone estimates for Tulasewa pertain to a different period than those of Korokula and Koromani forests. The mean daily drainage (D) and rainfall (P) rates and their ratio has been added for comparison.*

Component	Pre-cyclone			Post-cyclone		
	Tulasewa	Korokula	Koromani	Tulasewa	Korokula	Koromani
P [mm]	1932	1617	1745	1858	1190	1224
ET [mm]	1765	1423	1423	981	979	983
D [mm]	167	194	322	877	211	241
n [days]	364	331	331	306	306	306
Average P [mm day-1]	5.3	4.9	5.3	6.1	3.9	4.0
Average D [mm day-1]	0.5	0.6	1.0	2.9	0.7	0.8
D/P	0.09	0.12	0.18	0.47	0.18	0.20

by inserting the values of P and D in Equation 6.11 for Koromani forest was only slightly higher (3.2 mm day^{-1}) than the dry season ET$_{pm}$ (3.0 mm day^{-1}) as derived from micro-meteorological measurements above Koromani forest for the period May – September 1991, lending some confidence to the D values for the Korokula and Koromani forest plots.

Wet season rainfall at Tulasewa forest was some 500 mm higher than that measured at Oleolega, and it was therefore not realistic to use the runoff coefficient obtained at the latter site to calculate D at the Tulasewa forest plot. Furthermore, the soil at Tulasewa forest remained wet throughout the 1991 dry season (Figures 6.4 and 6.5), since the tree density of the forest had been reduced considerably after the passage of cyclone Sina. As such drainage will have occurred throughout the post-cyclone period. To calculate D from Equation 6.11, estimates of post-cyclone ET were obtained from the pre-cyclone value of ET$_{pm}$, using a reduction factor (0.66) obtained from a comparison of post-cyclone and pre-cyclone ET$_{sm}$ values (Table 6.8). This factor may have been too high since the pre-cyclone ET$_{sm}$ was underestimated due to the presence of roots below the measurement depth, whereas the 1991 value may have been fairly accurate due to the reduced tree density (no water stress in top soil at any time). A summary of the results is presented in Table 6.9.

Chapter 7

Forest Micro-meteorology

7.1 Introduction

The chief advantage of micro-meteorological methods over the soil moisture and catchment water balance methods is that the magnitudes of the various components of the forest energy balance, and therefore evapotranspiration, may be established from relatively simple above and within canopy measurements of meteorological parameters (*e.g* radiation, temperature, humidity and wind speed) over short periods of time (*e.g.* 30-minute intervals).

The methods discussed in this chapter include the Bowen Ratio Energy Balance method (BREB method; Angus and Watts, 1984), the Temperature Fluctuation Energy Balance method (TFEB method; Tillman, 1972; De Bruin, 1982) and the more empirical Penman-Monteith method, which has already been discussed briefly in Chapter 5. The Penman open water evaporation (E_0) was used as a reference, because long-term E_0 values could be obtained from routine measurements of climatic variables by the Fiji Meteorological Service.

There are several restrictions to the application of the energy balance methods. Both the BREB and the TFEB methods assume that all the energy fluxes act in the vertical (no advection) and that wind, temperature and humidity profiles are in equilibrium with the underlying surface. As such the research area should be flat and a large fetch is required in the upwind direction, and preferably in the downwind direction as well (Angus and Watts, 1984). This severely restricts the general application of such methods as forests in Fiji (and elsewhere) tend to be planted in patches in more or less steeply dissected terrain. However, the vegetation around the sites selected for micro-meteorological measurements within the present framework (Tulasewa and Koromani) was thought to be sufficiently homogeneous for the application of the BREB and TFEB methods, but the topography was not entirely flat, which will have influenced the results to some extent.

Several working papers were prepared by MSc students from FES-VUA on the determination of surface roughness characteristics, energy balance components and evapotranspiration rates for both the Tulasewa (Beekman, 1992; Frumau, 1993) and the Koromani forest (Harkema, 1994; Opdam, 1993; Van Well, 1993a). The results presented in this chapter rely partly on their work (*e.g.* calibration of instruments), but also include new data (*e.g.* wet season evapotranspiration rates for Tulasewa Forest).

To limit the size of this chapter the theory underlying the various methods will be discussed only briefly and the reader is referred to the work of Thom (1975), Monteith (1976), De Bruin (1982), Brutsaert (1982) and Frumau (1993) for more comprehensive discussions.

7.2 Methods and Procedures

Above and within canopy micro-meteorological measurements were made in the Tulasewa forest plot from November 29, 1989 until November 28, 1990, when the micro-meteorological set-up and the forest were destroyed by cyclone Sina, and at the meteo site near the Koromani forest plot from April 27, 1991 until September 20, 1991. The instrumentation of the meteorological towers was similar in both forests and the configurations of the instruments are given in Table 7.1. Details on the instruments are given below.

Short-wave solar radiation and **reflected radiation** were measured with the types of pyranometer and albedometer which have already been discussed in Section 5.2.

Net radiation was measured with a net radiometer (Radiation and Energy balance Systems Inc., Model Q*5) placed level within 1° on a support arm extending 1.5 m from the mast. The position of the radiometer was such that the shadow of the mast could not interfere with the measurements. The calibration given by the manufacturer (13.7 W m^{-2} mV^{-1}) was used throughout the measurement period. The instrument was supplied with heavy duty polyethylene windshields, which were replaced in June 1990. Recalibration of the instrument after replacement of the domes was not possible and a small error (up to 3%) could have been introduced. The net radiometer was damaged during the passage of cyclone Sina and a new instrument was used for the measurements in Koromani forest.

The **soil heat flux** was measured with soil heat flux plates placed at a depth of 2 cm below the soil surface. Care was taken not to disturb the litterlayer above the flux plates during installation. Details on the plates were provided in Section 5.2.

Air temperatures and **relative humidities** were measured at three levels above the canopy and at one level within the canopy using the following instruments. Three pairs of fast response thermocouples (chromium–constantane) were used to measure wet and dry bulb temperatures above the canopy whereas one thermocouple (dry) was placed within the canopy. The wet bulb temperature was measured with a thermocouple of which the junction was kept moist by a thin cotton wire connected to a reservoir filled with rain water (electrical conductivity ≈ 2 μS cm^{-1}). Profiles of air temperature and relative humidity were also measured with non-aspirated Rotronic temperature and humidity probes (Section 5.2). All instruments were calibrated before installation at their respective levels within and above the canopy, followed by recalibrations during the measurement period by shifting the position of one of the instruments (*e.g.* within canopy rotronic) to higher levels for periods of several days at a time. As a back-up system, wet and dry bulb temperatures were measured with aspirated psychrometers equipped with radiation shields made at the FES-VUA. The temperatures were measured using Negative Temperature Coefficient (NTC) resistors. The wet and dry bulb sensors were placed in separate tubes to avoid interference between sensors, and the wet bulb sensor was kept moist by a cotton wick immersed in a reservoir filled with rain water. Aspiration was provided by a miniature electric fan. Details on the calibration of the instruments in Tulasewa Forest have been provided in

Table 7.1: *Configuration of instruments in the meteorological masts in the Tulasewa forest plot between ([a]) November 1989 – April 1990 and ([b]) April – November 1990, and in that at the Koromani meteo site between April – September 1991.*

Level	**Instruments**	**Tulasewa**[a] *Height*	**Tulasewa**[b] *Height*	**Koromani** *Height*
Tree height		*11.5 m*	*12.5 m*	*17.5 m*
High, z_3	Wind vane	12.5 m	21.9 m	32.3 m
	Anemometer	12.5 m	21.1 m	32.1 m
	Rotronic	12.5 m	21.1 m	32.1 m
	Psychrometer	12.5 m	21.2 m	31.8 m
	Thermocouples (dry-wet)		21.2 m	31.9 m
Mid, z_2	Anemometer	11.0 m	17.0 m	27.0 m
	Rotronic		17.0 m	27.0 m
	Psychrometer		17.0 m	27.0 m
	Thermocouples (dry-wet)		17.0 m	26.9 m
Low, z_1	Anemometer	9.5 m	13.0 m	24.1 m
	Rotronic	9.5 m	13.0 m	24.1 m
	Psychrometer	9.5 m	13.0 m	24.1 m
	Thermocouples (dry-wet)		13.0 m	24.0 m
	Pyranometer	11.0 m	12.8 m	21.9 m
	Albedometer		12.6 m	21.9 m
	Net radiometer	11.0 m	12.5 m	21.9 m
	Rain gauge	8.7 m	11.8 m	22.0 m
Forest, z_f	Rotronic		6.0 m	12.8 m
	Psychrometer		6.1 m	12.8 m
	Thermocouple (dry)		6.1 m	12.8 m
Tree	Thermistor		1.5 m	2.0 m
Litter	Thermistor	0.0 m		
Soil	Flux plates	-2 cm (1)	-2 cm (2)	-2 cm (2)
	Thermistor	-2 cm	-2 cm	-2 cm
	Thermistor		-10 cm	

the working papers by Beekman (1992) and Frumau (1993), whereas those for the Koromani forest have been provided by Opdam (1993), Van Well (1993a) and Harkema (1994).

Profiles of above canopy **wind speed** were obtained using 3 anemometers (see Section 5.2 for instrument details) mounted on 0.8 m support arms pointing towards the main wind direction (SE). No corrections were made for overspeeding or stalling. **Wind direction** was measured with a potentiometer windvane (see Section 5.2 for details) placed on top of the mast. As it was difficult to align the arrow on the windvane exactly to the true North, measurements may again have a systematic error of about 5°.

Litter and **soil temperatures** were measured with thermistors (Campbell Scientific Ltd. 107B) placed at 0 cm, 2 cm and 10 cm (in Tulasewa forest only) below the soil surface. A fourth thermistor was implanted in the bole of a tree with near average dimensions at a depth of 4–5 cm with reference to the bark surface. In each forest the sensor was implanted in the bole of a tree with near average dimensions (Tree no. 57 and 219 in Tulasewa (Frumau, 1993) and Koromani forests (Opdam, 1993), respectively). The accuracy of the thermistors was typically better than 0.2 °C.

Above canopy **rainfall** was measured with a Campbell Scientific tipping bucket raingauge (model ARG100) with a resolution of 0.2 mm and a funnel diameter of 25.5 cm. As explained in Section 6.2 additional rainfall measurements were made in nearby clearings using manual gauges and mechanical recorders.

All instruments were connected to a Campbell 21X micrologger in combination with a multiplexer system (Campbell Scientific Inc., USA). Half-hourly averages, standard deviations and correlation coefficients between the various thermocouple temperatures were determined from 5-minute means of temperature measurements, obtained at a sampling frequency of 2 seconds, to minimize the influence of trends on the standard deviations (De Bruin *et al.*, 1993). The other instruments were sampled with a 30-second interval to obtain 30-minute averages and standard deviations. Total rainfall was recorded every five minutes as the sum of 30-second measurements. The data were temporarily stored on a Campbell Scientific SM716 storage module and later transferred to floppy disk.

Additional **tree bole temperatures** were measured using pre-calibrated NTC resistors, implanted at various heights and depths in the bole. The sensors were connected to a datalogger developed at FES-VUA. The measurements were made at a 30-minute interval and started on May 2, 1990, and May 7, 1991, in the Tulasewa forest plot and at the Koromani meteo site, respectively. Measurements were made on tree no. 57 at heights of 1.5 m (implantation depths: 2 and 8.5 cm with reference to the bark surface) and 7.0 m (implantation depths: 2 and 5 cm) in the Tulasewa forest plot, and on tree no. 219 at heights of 2.0 m and 6.5 m (implantation depths: 0, 3 and 7 cm) and 15.5 m (implantation depths: 0 and 2 cm, from July 17 onwards) at the Koromani meteo site.

An automatic porometer (see also Section 5.2) was used to determine half-hourly values of the **stomatal resistance** of pine needles from a single young tree (age 3–4 years) in the grassland and from a tree in Koromani forest at heights of 12.7 m, 15.7 m and 19.0 m. No such measurements were made in the Tulasewa forest plot since the instrument only became available after the forest had been destroyed by cyclone Sina. Access to the canopy of Koromani forest was provided by a scaffolding tower with a height of 20.6 m, which was also used for the micro-meteorological measurements. Measurements were made on nine days between July 2 and September 20, 1991, with the earliest measurement at 5:55 h and the latest at 21:45 h. The stomatal resistances of five needle sets within each level were measured at 30–60 minute intervals. The porometer cup was designed to be used on broad leaved species. Measurements could therefore not be made on single needles as leakage would occur along the edges. However, the stomatal resistance could be measured by aligning several needles in such a way that a smooth surface was formed on which the cup of the porometer could be placed. To test whether leakage occurred a set of dead needles was aligned in a similar way and the cup was placed on the needles after which the relative humidity in the cup was lowered to a much lower level than that of the ambient air. Because the dead needles were very dry, a rise in humidity within the cup would indicate leakage. Leakage was not observed at low wind speeds, but occurred when wind speeds within the canopy exceeded 3–4 m s^{-1} and measurements were stopped accordingly.

7.3 Forest Aerodynamic Characteristics

7.3.1 Theory

Near the earth surface vertical fluxes of mass and heat are mainly transported by turbulence produced by the friction between horizontal winds and the surface (Thom, 1975). In a neutral surface layer, characterized by the absence of buoyant eddies, where the Coriolis effect can be ignored and the momentum flux may be considered independent of height, the vertical distribution of the wind speed over a uniform, flat surface can be described by the logarithmic wind profile equation (Thom, 1975):

$$u(z) = \frac{u_*}{k} \cdot \ln \frac{z}{z_0} \tag{7.1}$$

where $u(z)$ is the horizontal wind speed at height z above the surface, u_* is the friction velocity, k is the Von Karman's constant and z_0 is the roughness length, which depends on the average height, spatial distribution, shape, flexibility and mobility of the roughness elements and ranges from $2 \cdot 10^{-4}$ m for ice and mud flats to several metres for tall forests and urban areas (Arya, 1988). For a surface covered with tall vegetation, the logarithmic wind profile is lifted to a new reference level, lying somewhere between the surface and the height of the vegetation h. The height of this level is called the zero plane displacement length (d) and, for tall vegetation, Equation 7.1 needs to be modified (Thom, 1975) to:

$$u(z) = \frac{u_*}{k} \cdot \ln \frac{z-d}{z_0} \tag{7.2}$$

The zero plane displacement length for a given vegetation type depends on the height and areal density of the elements, being low for scattered vegetation (*e.g.* savanna) and approaching h for very dense canopies (Arya, 1988). It is unrealistic to assume zero wind velocity below the level $d + z_0$, as momentum is absorbed gradually over the height of the vegetation and the logarithmic wind profile, as described by Equation 7.2, does develop not immediately above the level $d + z_0$, but at a certain distance from the canopy (Hicks, 1985) where the influence of individual roughness elements can be discarded. Wind profile measurements should therefore be made at sufficient height above the canopy, but within the layer of constant flux (Thom, 1975).

It is common to express z_0 and d in relation to the mean or median vegetation height and Stanhill (1969) and Szeicz *et al* (1969) derived the following empirical relations:

$$\log(d) = 0.979 \log(h) - 0.154 \tag{7.3}$$

$$\log(z_0) = 0.997 \log(h) - 0.883 \tag{7.4}$$

Jarvis *et al.* (1976) gave an overview of the aerodynamic characteristics for temperate coniferous forests with median tree heights ranging from 4.5 to 28.0 m and observed that the ratio of z_0/h ranged from 0.02 to 0.14, whereas d/h ranged from 0.61 to 0.92 over a fairly wide range of stable and unstable atmospheric conditions.

The Richardson number (Ri) is the ratio of the buoyancy energy production term to the windshear energy production term in the turbulent kinetic energy budget. It is dimensionless and provides a good indication of the local turbulent structure of the air. As such it may be used as a criterium to select wind data close to neutral atmospheric conditions for the determination of z_0 and d. If temperatures T_1 and T_2 and wind speeds u_1 and u_2 are measured at levels z_1 and z_2 above the surface, Ri for the intermediate layer can be calculated from the following equation (Thom, 1975):

$$Ri = \frac{g}{T} \cdot \frac{(T_2 - T_1 + \Gamma \cdot (z_2 - z_1))(z_2 - z_1)}{(u_2 - u_1)^2} \tag{7.5}$$

where g is the gravitational acceleration, T is the mean temperature of the layer and Γ is the adiabatic lapse rate (0.01 K m^{-1}). Ri is close to zero under near-neutral conditions as the buoyant energy production term approaches zero, whereas Ri is negative for stable atmospheric conditions and positive for unstable conditions (Thom, 1975).

There are several methods for the estimation of z_0 and d. The graphical and analytical methods, which are basically similar, require knowledge of the above canopy wind speed distribution and are based on the following assumptions (Thom, 1975):

- All momentum is absorbed at the level $d + z_0$; hence wind speeds are assumed zero below this level.
- The wind profile immediately above the level $d+z_0$ is logarithmic under neutral atmospheric conditions.

With the **graphical method** proposed by Thom (1975), the level $d + z_0$ can be found by plotting averages of $u(z)$, measured under neutral atmospheric conditions at a minimum of three levels above the canopy, against z and drawing a logaritmic curve through the data points. The intercept of this line with the z-axis ($u(z) = 0$) represents the value of $d + z_0$ (Thom, 1975). As the drawing of the curve is done by eye, this method is somewhat subjective. Estimates of z_0 and d can then be obtained by elimination of the unknown u_* in Equation 7.2 using ratios of $u(z)$ measured at two levels according to:

$$\frac{u(z_2)}{u(z_1)} = \ln \frac{\frac{z_2-d}{z_0}}{\frac{z_1-d}{z_0}} \tag{7.6}$$

A matrix of $u(z_2)/u(z_1)$ can be prepared for various combinations of z_0 and d and because $d + z_0$ is derived from the graphical method, fairly accurate values of d, and therefore also z_0, may be obtained by searching for the combination of z_0 and d in the matrix, that equals the ratio of measured wind speeds at levels z_2 and z_1.

With the **analytical method** proposed by Robinson (1962) Equation 7.2 is solved numerically for d, z_0 and u_* by minimizing the square of the vector of errors with the condition that the partial derivatives with respect to u_*/k, d and z_0 are zero.

Another method involves the fitting of a straight line through a semi-logarithmic plot of $u(z)$ against $\ln(z - d)$ for various values of d. The optimum value of d is that for which the Pearson product-moment correlation coefficient is highest, and $\ln z_0$ is

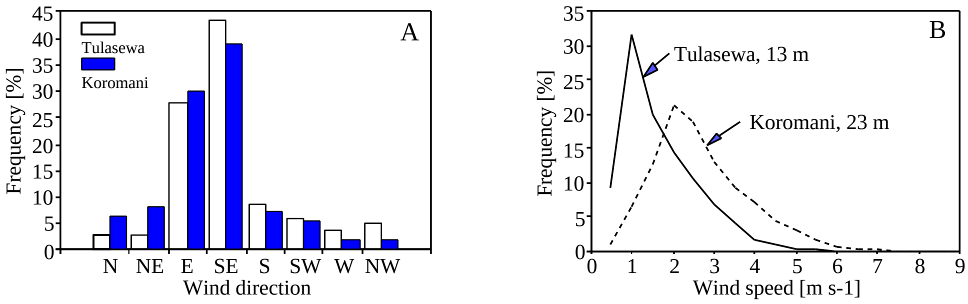


Figure 7.1: *Frequency distributions of 30-minute average wind directions (A) and wind speeds (B) for Tulasewa (n= 16817) and Koromani (n= 6771) forests.*

then found as the intercept of that line with the $\ln(z - d)$ axis (Thom, 1975; Frumau, 1993).

Mass conservation methods (*e.g.* Molion and Moore, 1983; De Bruin and Moore, 1985) require knowledge of both above and within canopy wind speed distributions. In the present case the latter were not available and these methods could therefore not be applied without introducing uncertainties caused by the assumption of a within canopy wind speed distribution (Frumau, 1993).

7.3.2 Wind Speed and Direction

Frequency distributions of wind directions and speeds, measured just above the forest canopies at Tulasewa and Koromani forests, are shown in Figure 7.1A and 7.1B, respectively. The wind direction was predominantly east to southeast and wind speeds were low, seldomly exceeding 5 m s^{-1} (Figure 7.1B). The wind speed as measured at 24.1 m at the Koromani forest meteo site averaged 3.0($\pm$0.8) m. The diurnal cycles of wind speeds were similar to those observed at Nadi Airport (Section 2.4.4) with low values at night and higher values during daytime with a maximum shortly after noon.

7.3.3 Quantification of Aerodynamic Characteristics of Study Forests

Above canopy wind speeds were measured at or at less than the minimum number of levels required for the determination of z_0 and d with most of the previously discussed any methods, and the use of the more sophisticated models (*e.g.* mass conservation methods of Molion and Moore (1983), De Bruin and Moore (1985)) to obtain the surface roughness parameters for Tulasewa and Koromani forests was not justified therefore. As such, d and z_0 were determined using the graphical method. The Richardson number was calculated for each half-hour period and wind profiles were selected for neutral conditions ($-0.01 < Ri < 0.01$). Profiles having wind speeds of less than 1 m s^{-1} at the lowest level (z_1) were excluded, since these may have been influenced by the proximity to the canopy (Frumau, 1993; Opdam, 1993). In view of the undulating topography of the areas surrounding the masts (both masts were on SE facing slopes), local inhomogeneities in the forest canopies (small gaps, roads and stream valleys) and fetch limitations, a dependency of z_0 and d on wind direction was

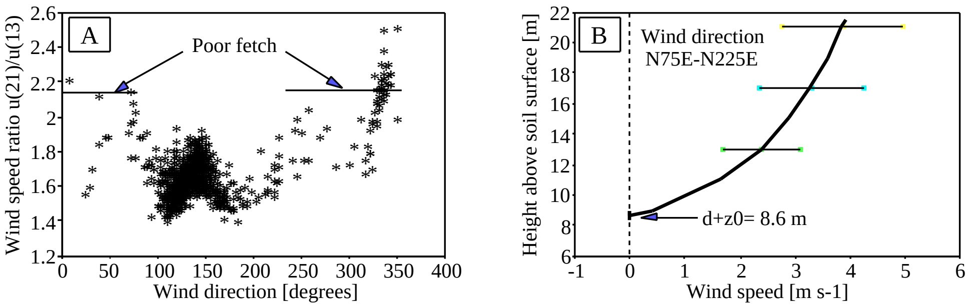


Figure 7.2: *Ratio of* $u(21.1)/u(13.0)$ versus *the wind direction (A), and the curve fitted through the mean wind profile (B; standard deviations represented by vertical and horizontal bars) to determine the level of* $d + z_0$ *(B) for Tulasewa forest according to the graphical method.*

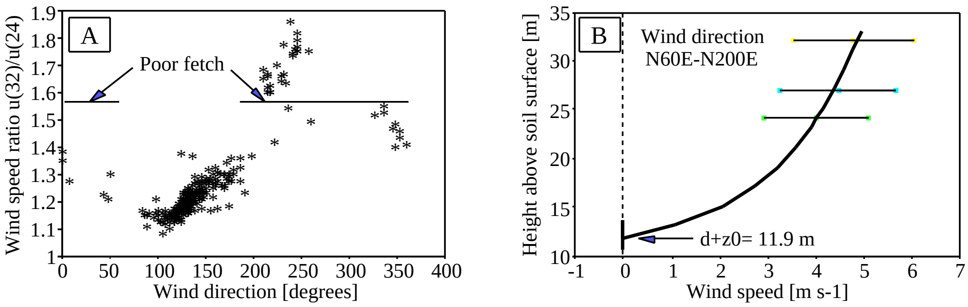


Figure 7.3: *Ratio of* $u(32.1)/u(24.1)$ versus *the wind direction (A), and the curve fitted through the mean wind profile (B; standard deviations represented by horizontal bars) to determine the level of* $d + z_0$ *(B) for Koromani forest according to the graphical method.*

expected. To test this the ratios of $u(z_3)/u(z_1)$ (a measure of the shape of the wind profile) were plotted against wind direction as shown in Figures 7.2A and 7.3A for the Tulasewa and Koromani sites, respectively. These diagrams clearly show that the shape of the profiles, and therefore the magnitudes of z_0 and d, varied with wind direction, with large changes in the ratios observed for those wind directions where the fetch changed from sufficient to poor. A further selection was made therefore, selecting only those wind profiles for which the wind direction was such that the fetch was sufficient. Hence wind profiles for wind directions between N225E–N75E at Tulasewa forest, and N200E–N60E at Koromani forest were excluded, resulting in 971 and 244 variable wind profiles, respectively. The average wind speeds and standard deviations measured at levels z_1, z_2 and z_3 at Tulasewa and Koromani forests have been plotted against height to determine the levels of $d + z_0$ in Figures 7.2B and 7.3B, respectively. Logarithmic curves were fitted by trial and error and the intercepts with the Y-axis provided information on the mean levels and range of $d + z_0$. This resulted in average values of $8.6(\pm 0.5)$ m and $11.9(\pm 1.5)$ m for $d + z_0$ in Tulasewa and Koromani

Table 7.2: *Matrix of $u(21.1)/u(13.0)$ values calculated for various combinations of d and z_0. Ratios close to the average ratio of measured wind speeds at Tulasewa forest are shown in bold typeface, whereas the most likely combination of z_0 and d is shadowed.*

	Displacement length d, [m]													
z0 [m]	**5.7**	**5.9**	**6.1**	**6.3**	**6.5**	**6.7**	**6.9**	**7.1**	**7.3**	**7.5**	**7.7**	**7.9**	**8.1**	**8.3**
0.8	1.335	1.346	1.357	1.370	1.383	1.397	1.412	1.429	1.447	1.466	1.487	1.509	1.534	1.561
0.9	1.354	1.365	1.378	1.391	1.406	1.421	1.438	1.456	1.475	1.496	1.519	1.544	1.571	**1.601**
1	1.372	1.385	1.399	1.413	1.429	1.445	1.463	1.483	1.504	1.527	1.552	1.579	**1.609**	**1.642**
1.1	1.391	1.405	1.419	1.435	1.452	1.470	1.489	1.510	1.533	1.558	1.585	**1.615**	**1.648**	1.684
1.2	1.410	1.424	1.440	1.457	1.475	1.494	1.515	1.538	1.563	1.590	**1.619**	**1.652**	1.688	1.728
1.3	1.429	1.444	1.461	1.479	1.499	1.519	1.542	1.567	1.593	**1.623**	**1.655**	1.690	1.730	1.773
1.4	1.448	1.465	1.483	1.502	1.523	1.545	1.569	1.596	**1.625**	1.656	1.691	1.730	1.773	1.821
1.5	1.468	1.485	1.504	1.525	1.547	1.571	1.597	**1.626**	1.657	1.691	1.729	1.771	1.818	1.870
1.6	1.488	1.506	1.527	1.549	1.572	1.598	**1.626**	1.657	1.690	1.727	1.768	1.814	1.865	1.922
1.7	1.508	1.528	1.550	1.573	1.598	**1.626**	1.656	1.689	1.725	1.765	1.809	1.859	1.914	1.977
1.8	1.529	1.550	1.573	1.598	**1.625**	1.654	1.687	1.722	1.761	1.804	1.852	1.906	1.967	2.036

Theoretical ratio of wind speeds measured at 21.0 m and 13.0 m

forests, respectively.

To obtain individual estimates of d and z_0, the ratios of average wind speeds at the upper, middle and lower levels were calculated and matrices were prepared for each forest using Equation 7.6 to calculate theoretical ratios for various combinations of z_0 and d, keeping in mind that for temperate pine forests z_0 and d are usually in the range of $0.02h$–$0.14h$ and $0.6h$–$0.9h$, repectively (Jarvis *et al.*, 1976). The ratio $u(z_3)/u(z_1)$ averaged $1.625(\pm 0.098)$ and $1.200(\pm 0.060)$ in Tulasewa and Koromani forests, respectively, and using the matrices shown in Tables 7.2 and 7.3 in combination with the previously determined averages of $d + z_0$, resulted in the estimates of d and z_0 given in Table 7.4 for the respective mean wind profiles. The table also includes earlier estimates by Beekman (1992), Frumau (1993), Opdam (1993) and Harkema (1994) for short selected periods from the overall data set.

Even within the reduced data set, for which the fetch was considered sufficient, some dependency of roughness parameters on wind direction existed due to topography and inhomogeneities in the respective forest canopies, with ratios of $u(z_3)/u(z_1)$ ranging from 1.4 to 1.9 at Tulasewa and from 1.1 to 1.4 in Koromani (see Figures 7.2A and 7.3A). Higher than average ratios of $u(z_3)/u(z_1)$, pointing to relatively flat wind profiles, were observed for wind directions around N140E in Tulasewa forest and between N160–180E at Koromani forest. However, the scatter of the wind speed ratios was considerable and, as the resulting variations in z_0 and d were thought to be within 15% of the averages given in table 7.4, no further classification with respect to wind direction was made.

Frumau (1993) also calculated values for d and z_0 for Tulasewa forest using the analytical and mass conservation methods referred to earlier. The analytical methods produced widely varying results, which were sometimes physically unrealistic (*e.g.* negative values of d). However, if the latter were excluded averages of d and z_0 of 7.0 m and 1.5 m, respectively, were obtained which were similar to those presently obtained with the graphical method. Application of the analytical method of Robinson (1962) to various classes of wind speeds and directions indicated that the roughness parameters

Table 7.3: *Matrix of $u(32.1)/u(24.1)$ values calculated for various combinations of d and z_0. Values comparable to the measured $u(z_3)/u(z_1)$ ratios at Koromani forest are shown in bold typeface, whereas the most likely combination of z_0 and d is shadowed.*

	Displacement length d, [m]													
z0 [m]	**9.0**	**9.2**	**9.4**	**9.6**	**9.8**	**10.0**	**10.2**	**10.4**	**10.6**	**10.8**	**11.0**	**11.2**	**11.4**	**11.6**
0.8	1.145	1.147	1.149	1.152	1.154	1.157	1.159	1.162	1.165	1.168	1.170	1.174	1.177	1.180
0.9	1.151	1.153	1.156	1.158	1.161	1.163	1.166	1.169	1.172	1.175	1.178	1.181	1.185	1.188
1.0	1.157	1.159	1.162	1.164	1.167	1.170	1.173	1.176	1.179	1.182	1.185	1.189	1.192	**1.196**
1.1	1.162	1.165	1.168	1.170	1.173	1.176	1.179	1.182	1.186	1.189	1.192	**1.196**	**1.200**	**1.204**
1.2	1.168	1.171	1.173	1.176	1.179	1.182	1.186	1.189	1.192	**1.196**	**1.199**	**1.203**	1.207	1.211
1.3	1.173	1.176	1.179	1.182	1.185	1.189	1.192	**1.195**	**1.199**	**1.203**	1.206	1.210	1.214	1.219
1.4	1.179	1.182	1.185	1.188	1.191	1.195	**1.198**	**1.202**	**1.205**	1.209	1.213	1.217	1.222	1.226
1.5	1.184	1.187	1.190	1.194	**1.197**	**1.201**	**1.204**	1.208	1.212	1.216	1.220	1.224	1.229	1.233
1.6	1.189	1.193	**1.196**	**1.199**	**1.203**	1.207	1.210	1.214	1.218	1.222	1.227	1.231	1.236	1.241
1.7	1.195	**1.198**	**1.201**	**1.205**	1.209	1.212	1.216	1.220	1.225	1.229	1.233	1.238	1.243	1.248
1.8	**1.200**	**1.203**	1.207	1.211	1.214	1.218	1.222	1.227	1.231	1.235	1.240	1.245	1.250	1.255

Theoretical ratio of wind speeds measured at 32.1 m and 24.1 m

were independent of wind speed (range 1–5 m s^{-1}) but confirmed the dependency on wind direction for Tulasewa forest where d dropped sharply from 8.5(±2.0) m for the N110–130E interval to 5.7(±2.0) for the N130–150E interval, with a corresponding increase of z_0 from 0.7(±1.0) m to 2.4±1.3 m. The results of various mass conservation methods, (using a theoretical function; Cionco, 1965) to simulate the within canopy wind speed distribution) were comparable to those obtained with the graphical and analytical methods (Frumau, 1993). Estimates of 7.0 m for d and of 1.5 m for z_0 for the mean wind profile were obtained with the method of Molion and Moore (1983), whereas the method of De Bruin and Moore (1985) yielded less realistic averages of 5.1 m for d and 1.0 m for z_0 (Frumau, 1993). The mass conservation methods further indicated that d was highest for the N130–150E interval, in contrast to the results obtained with the analytical methods, whereas z_0 remained fairly constant regardless of wind direction. These uncertainties in the dependency of the roughnes parameters on wind direction supported the decision to use averages of d and z_0, rather than to express them as a function of wind direction.

The trees in the Tulasewa forest plot increased some 2.5 m $year^{-1}$ in height during the measurement period and it is therefore not realistic to assume that z_0 and d remained constant over longer periods of time. However, d/h and z_0/h may be considered fairly constant and these, in combination with measured growth rates (Chapter 11), were used in the calculations of the sensible heat flux with the temperature fluctuation energy balance method (Equation 7.24) and of the aerodynamic resistance for the Penman-Monteith method (Equation 5.4). Therefore z_0 increased from 1.3 m in December 1989 to 1.6 m in November 1990, with corresponding values for d increasing from 6.3 m to 7.4 m.

Koromani forest showed no significant increase in height and constant values of z_0 and d were used in the calculations throughout.

Table 7.4: *Summary of forest aerodynamic characteristics as obtained for various selected periods in Tulasewa and Koromani forests under neutral atmospheric conditions.*

Location & method	Wind direction	z0 [m]	d [m]	h [m]	z0/h	d/h	Remarks	Period	Author
TULASEWA FOREST									
Graphical	**N75-225E**	**1.5**	**7.1**	**12.7**	**0.12**	**0.56**	**All weather**	**May-Nov '90**	**Present study**
Graphical	SE	0.8	8.3	12.1	0.07	0.69	Cloudy day	14/5/90	Beekman, 1992
Graphical	SE	0.9	8.1	12.3	0.07	0.66	Sunny day	2/6/90	Beekman, 1992
Graphical	N	1.3	9.4	12.3	0.11	0.76	Rainy day	10/6/90	Beekman, 1992
Graphical	N90-270E	1.3	7.9	12.7	0.10	0.62	All weather	17-22/8/90	Frumau, 1993
Analytical	N90-270E	1.5	7.0	12.7	0.12	0.55	All weather	17-22/8/90	Frumau, 1993
M&M	N90-270E	1.5	7.0	12.7	0.12	0.55	All weather	17-22/8/90	Frumau, 1993
DB&M	N90-270E	1.0	5.1	12.7	0.08	0.40	All weather	17-22/8/90	Frumau, 1993
Empirical		*1.7*		*12.7*	*0.13*				*Szeicz et al., 1969*
Empirical			*8.4*	*12.7*		*0.69*			*Stanhill, 1969*
KOROMANI FOREST									
Graphical	**N60-200E**	**1.4**	**10.4**	**17.8**	**0.08**	**0.58**	**All weather**	**May-Sep '91**	**Present study**
Graphical	SE	0.9	10.2	17.8	0.05	0.58	All weather	Jun-Jul '91	Opdam, 1993
Graphical	SE	1.2	10.2	17.8	0.07	0.57	All weather	May-Jun '91	Harkema, 1993
Empirical		*2.3*		*17.8*	*0.13*				*Szeicz et al., 1969*
Empirical			*11.8*	*17.8*		*0.66*			*Stanhill, 1969*

M&M: Molion and Moore, 1983; DB&M: De Bruin and Moore, 1985.

7.4 Temperature and Relative Humidity

Dry season averages of temperature and relative humidity measured above grassland in the dry season of 1991 were presented in Chapter 5. Corresponding averages measured above Tulasewa (13 m) and Koromani (24 m) forests are presented in Table 7.5. Differences beteween the site were significant. However, these differences may be the result of differences between two seasons themselves as the dry season of 1990 was rather wet and that of 1991 fairly dry (*cf.* Table 6.2). The differences will be discussed in Chapter 9.

7.5 Forest Energy Balance

7.5.1 Introduction

The BREB and TFEB methods use the surface energy balance equation (Equation 7.7) which partitions the incoming energy minus various storage terms (A) between the sensible heat flux H and the latent heat flux λE (Thom, 1975):

$$R_n - D_a - G - J - P_{veg} = A = H + \lambda E \tag{7.7}$$

where R_n is the net radiative input, D_a is the horizontal flux divergence or advective energy flux, G the soil heat flux, J and P_{veg} the fluxes of energy going into aboveground physical and biochemical storages, respectively. Evaporation rates (E,

Table 7.5: *Ranges and averages (standard deviation between brackets) of temperature (°C) and relative humidity (%) measured above Tulasewa and Koromani forests during the dry seasons of 1990 and of 1991, respectively.*

Location	**T**	**Tmin**	**Tmax**	**n**	**RH**	**RHmin**	**RHmax**	**n**
Tulasewa Forest, 1990								
Range	18.8-26	13.5-24.5	19.3-30.9	132	67-98	44-98	81-100	132
Average	22.2 (1.4)	18.8 (2.0)	26.5 (2.1)	132	84 (6)	66 (11)	96 (4)	132
Koromani Forest, 1991								
Range	18.4-26.9	16.6-24.8	19.4-31.7	127	53-88	33-88	68-100	124
Average	22.9 (1.5)	20.4 (1.5)	26.1 (1.9)	127	70 (8)	61 (11)	89 (8)	124
Tulasewa <> Koromani	<***	<***	>*		>***	>***	>***	

Significance level: *: 0.10; **: 0.05; ***: 0.01

in mm s^{-1}) can be obtained by dividing the latent heat flux (W m^{-2}) by the latent heat of vaporization of water (λ, in J kg^{-1}) and multiplying by the density of water (1.0 kg l^{-1}). Conventionally, fluxes in the downward direction (incoming) have a positive sign, whereas those in the upward direction (outgoing) are negative (Thom, 1975).

The advective energy flux was neglected in the energy balance as estimates of D_a can only be obtained if horizontal gradients of temperature, humidity and wind speed are known from simultaneous measurements made at a minimum of two sites (Thom, 1975). Under conditions of high R_n the error introduced by neglecting D_a was considered small as the upwind fetches of the Tulasewa and Koromani sites (about 75 and 47 times the height at which R_n was measured, respectively) were thought to be sufficient to limit advective energy inputs from surrounding dry grassland areas to a large extent. However, during periods of rainfall, when R_n is low and the wind direction may differ markedly from the SE, advective energy inputs from surrounding grasslands or the Ocean may play a significant role (*cf.* Section 6.4.1). Neglecting D_a under these circumstances may result in serious errors in H or λE.

The biochemical storage term P_{veg}, representing the use of energy in the production of biomass through photosynthesis, was neglected because it was difficult to measure and because it constitutes generally less than 1% of $R_s \downarrow$ (Brutsaert, 1982).

The magnitudes and the diurnal cycles of the various energy balance components for selected days, representing a range of climatic conditions (*e.g.* sunny, overcast and rainy), at the Tulasewa and Koromani sites will be presented in the following sections.

7.5.2 Net Radiation

The net radiation is the sum of downward and upward fluxes of short-wave and long-wave radiation (Brutsaert, 1982):

$$R_n = \underbrace{R_s \downarrow + \alpha R_s \uparrow}_{shortwave} + \underbrace{R_l \downarrow + R_l \uparrow}_{longwave} \qquad (7.8)$$

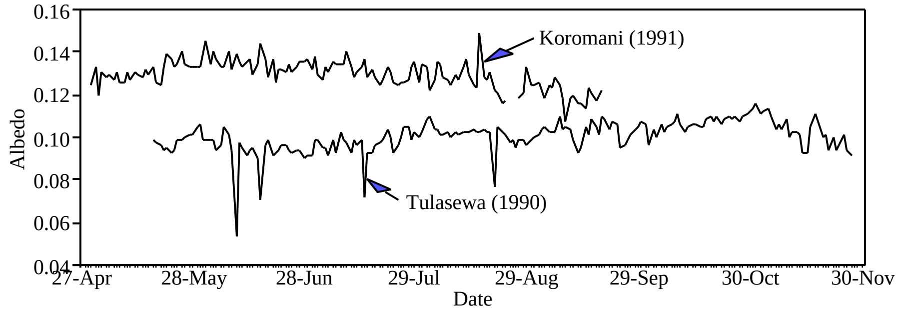


Figure 7.4: *Daily variation in the albedoes at Tulasewa and Koromani forest sites.*

where α represents the surface albedo for short-wave radiation. Incoming radiation consists of direct beam and diffuse short-wave solar radiation and of long-wave sky radiation. Outgoing radiation consists of reflected radiation and terrestrial long-wave radiation. The amount of reflected radiation depends both on the solar radiation intensity and on surface characteristics (*e.g.* albedo, *cf.* Section 5.4.1). The short-wave component of the net radiation is zero at night and the nigthtime R_n is therefore determined by the magnitude of the long-wave components. The opposite is true during daytime when the net short-wave component is much larger than the net long-wave component.

Both downward and upward fluxes of short-wave radiation were measured with the albedometer at Tulasewa and Koromani sites and the average dry-season value for α could therefore be calculated from the ratio of their daily totals. The daily variations in the albedoes of Tulasewa and Koromani forests are shown in Figure 7.4. The average albedo for Tulasewa forest over the period May 17 – November 27, 1990 was 0.100($\pm$0.007) (n= 195), whereas that for Koromani forest over the period April 30 – September 19, 1991, was significantly higher at 0.126($\pm$0.008) (n= 123). These values are in the range (0.08–0.14) found for temperate pine forests by Jarvis *et al.* (1976). At Tulasewa forest low α-values (down to 0.05) were observed when the canopy was wet, but this was not observed at Koromani forest. Such differences between forests may be caused partly by differences in canopy structure/density between the young and mature forest (Jarvis *et al.*, 1976). Furthermore, the canopy of Koromani forest had been severely damaged by cyclone Sina, which may also have influenced the 1991 value of α to some extent. The diurnal courses of α for Tulasewa and Koromani forests are shown in Figure 7.5.

Because α was fairly constant, R_n may be related to $R_s\downarrow$ empirically using a linear regression equation (Jarvis *et al.* 1976). The resulting expressions for the Tulasewa and Koromani forest sites based on half-hourly data are given by Equations 7.9 and 7.10, respectively.

$$R_n = -21.73(\pm 16.38) + 0.866(\pm 0.001)\cdot R_s\downarrow \\ \text{n}= 7646,\ \text{r}^2 = 1.00 \tag{7.9}$$

$$R_n = -39.99(\pm 21.01) + 0.846(\pm 0.001)\cdot R_s\downarrow \\ \text{n}= 5938,\ \text{r}^2 = 0.99 \tag{7.10}$$

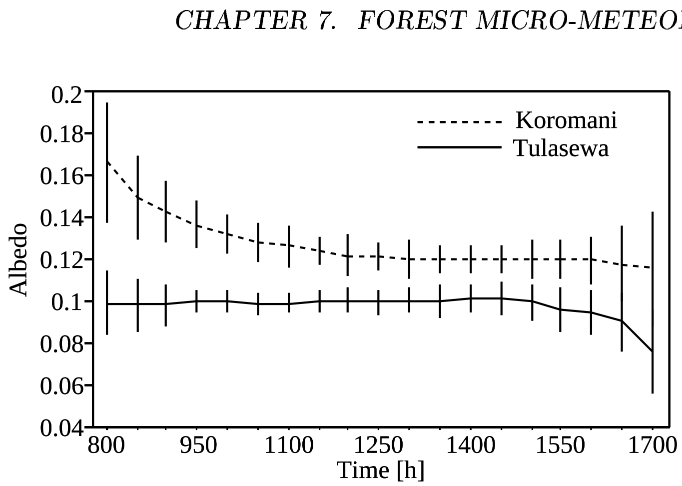


Figure 7.5: *Average diurnal courses and standard deviations (vertical bars) of the albedo at the Tulasewa and Koromani forest sites.*

Due to cracking of the plastic domes moisture entered the net radiometer in Tulasewa forest during a four week period in July and August 1990, and R_n during this period was therefore calculated using Equation 7.9. The net radiometer at the Koromani forest site was installed two weeks later than the other micro-meteorological equipment, and Equation 7.10 was therefore used to calculate R_n for this period.

Not all wavelengths are equally absorbed by vegetation (Ross, 1975). To obtain some insight into these differences, the albedo of photosynthetically active radiation (400–700 nm, α_{par}) for Koromani forest was determined on July 12 (14:00 h) from the ratio of reflected PAR, as measured at seven locations around the tower above the canopy with ceptometer held inverted, to incoming PAR as measured with the instrument above the canopy. This resulted in an α_{par} of 0.04, which is comparable to that given for temperate coniferous forests (0.03) by Ross (1975). The difference between α (300–2500 nm) and α_{par} indicates that reflection occurs mainly at wavelengths higher than 700 nm. Profiles of PAR were measured along the respective meteorological towers as shown in Figure 7.6. The profile for Tulasewa forest represents the average of two profiles measured on June 28, 1990, between 13:00 h and 13:30 h under clear sky conditions, whereas that for Koromani forest was the average of four replications of three profiles measured at different times on July 12, 1991, between 9:00 h and 15:00 h, againd during clear sky conditions. The profiles indicate that a large portion of PAR was absorbed by the foliage in the upper canopy. Vose and Swank (1990) assessed the vertical distribution of leaf area by ceptometer PAR measurements in a 32-year-old *Pinus strobus* plantation forest in North Carolina, USA, with LAI (3.6 m^2 m^{-2}) similar to that of the forests presently studied. The pattern observed was similar to that shown in Figure 7.6, with a sharp decrease of Q_z/Q_0 within the upper canopy from 0.9 at 26 m to less than 0.3 at 20 m. The PAR fraction remained fairly constant at about 0.05 below the canopy.

Diurnal patterns of $R_s \downarrow$, $\alpha R_s \uparrow$, R_n and the long-wave component of R_n for selected days with clear sky, overcast sky, and rainy conditions in Tulasewa and Koromani forests are shown in Figures 7.7 and 7.8, respectively. The net long-wave component was calculated as the difference of R_n and the short-wave component. The long-wave component remained negative throughout the day under all climatic con-

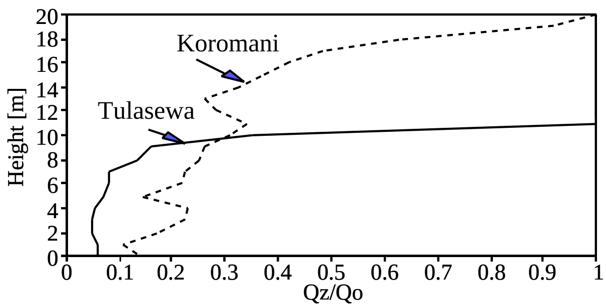


Figure 7.6: *Average profiles of PAR measured along the towers in Tulasewa and Koromani forests, expressed as the ratio of PAR at height z within the canopy* (Q_z) *to that measured above the canopy* (Q_0).

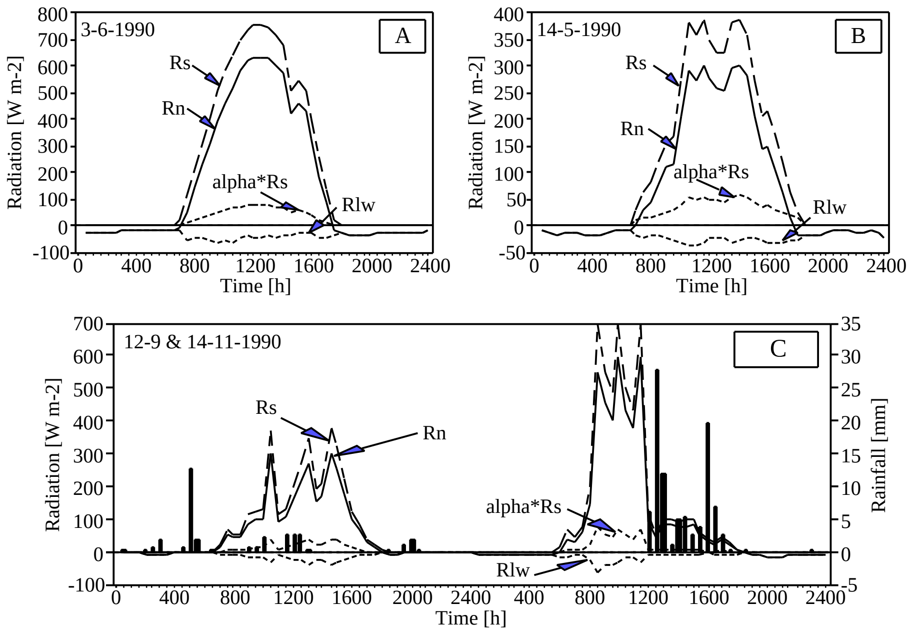


Figure 7.7: *Diurnal patterns of* $R_s \downarrow$, $\alpha R_s \uparrow$, R_n *and the long-wave component* (R_{lw}) *of* R_n *for selected days with clear sky (A), overcast sky (B), and rainy conditions (C) in Tulasewa forest.*

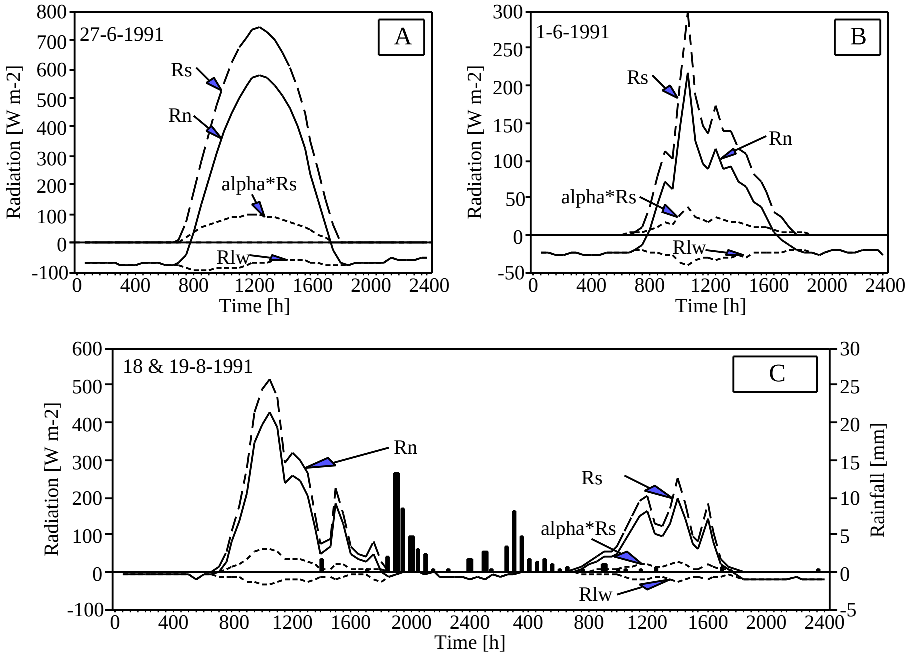


Figure 7.8: *Diurnal patterns of $R_s \downarrow$, $\alpha R_s \uparrow$, R_n and the long-wave component (R_{lw}) of R_n for selected days with clear sky (A), overcast sky (B), and rainy conditions (C) in Koromani forest.*

ditions, with minimum values in the mornings under clear skies. However, downward fluxes of long-wave radiation (emitted by clouds) resulted in less negative values of the net long-wave component, whereas it approached zero during periods of high rainfall (Figures 7.7C and 7.8C).

7.5.3 Physical and Biochemical Storage Terms

The total physical energy storage (J) within a column of unit cross-sectional area extending from the soil surface to the level at which R_n is measured can be separated into three terms:

$$J = J_h + J_w + J_{veg} \tag{7.11}$$

where J_h and J_w are the sensible and latent heat storage in the air within the stand, respectively, and J_{veg} is the rate of change in the heat content of the above-ground part of the vegetation (Thom, 1975). As most of the energy stored in each of these components during daytime will be released again during nighttime, the total energy storage may be negligible on a daily basis. However, on a half-hourly basis the storage in these components cannot be neglected (Stewart and Thom, 1973), especially during periods of low R_n and rapid changes in temperature (*e.g.* sunrise, sunset). The magnitudes of J_h and J_w are described by Equations 7.12 and 7.13, respectively (Thom, 1975):

$$J_h = \int_0^{z_{Rn}} \rho c_p \frac{\partial T}{\partial t} \cdot dz \tag{7.12}$$

$$J_w = \int_0^{z_{Rn}} \rho c_p \frac{\partial q}{\partial t} \cdot dz \tag{7.13}$$

where z is the height above the soil surface, z_{R_n} is the height of the R_n measurement, ρ and c_p are the density and heat capacity of the air, t is the time, and T and q are the temperature and specific humidity of the air, respectively (see Appendix 22.2 for details). Similarly, the amount of heat stored in the vegetation is described by Equation 7.14:

$$J_{veg} = \int_0^{h} \rho_{veg} c_{veg} \frac{\partial T_{veg}}{\partial t} \cdot dz \tag{7.14}$$

where h is the mean vegetation height, ρ_{veg} and c_{veg} are the density and specific heat of the vegetation, and T_{veg} is the temperature of the vegetation.

Assuming that ρ and c_p may be considered constant over the height of the air column, and with t= 1800 s for half-hourly measurements, the expressions for J_h and J_w may be simplified to respectively (Thom, 1975):

$$J_h = \frac{c_p \cdot \rho \cdot z_{R_n}}{1800} \Delta T \tag{7.15}$$

$$J_w = \frac{\lambda \cdot \rho \cdot z_{R_n}}{1800} \Delta q \tag{7.16}$$

and the expression for J_{veg} may be simplified to Equation 7.17 by substitution of the integral of $\rho_{veg} \cdot dz$ from $z = 0$ to $z = h$ by the mass of the vegetation per unit area (fresh biomass, M_{veg}).

$$J_{veg} = \frac{c_{veg} \cdot M_{veg}}{1800} \Delta T_{veg} \tag{7.17}$$

In these expressions ΔT and Δq represent the rates of changes in representative temperature and specific humidity values for the whole column, whereas ΔT_{veg} is the rate of change of the mean temperature of the biomass.

Within-canopy 30-minute averages of T and q were obtained at heights of 6.1 m and 12.8 m in Tulasewa and Koromani forests, respectively. Figure 7.6 has shown that most PAR had already been absorbed above these levels. Therefore the values of T and q measured at these heights were assumed representative for the conditions within the forests and were subsequently used to calculate J_h and J_w.

For the calculation of J_{veg}, data on the biomass, its temperature and c_{veg} are required. Values for the oven-dry standing biomasses of the Tulasewa and Koromani forest plots were taken from Chapter 11 representing estimates of 7.0 kg m^{-2} and 14.6 kg m^{-2}, respectively. The fresh biomass needed in the present calculations was obtained using conversion factors from Section 11.3.2, resulting in values of 14.9 and 28.1 kg m^{-2}, respectively. The heat capacity of fresh *Pinus caribaea* wood was unknown and was taken as 70% of the heat capacity of water, following Thom (1975) and McCaughey (1985). A large part of the forest biomass in the study plots was concentrated in the lower part of the tree stems (Chapter 11) and the tree bole temperatures measured at various heights and depths in the stems were averaged such that the distribution of the biomass with height was taken into account to obtain representative average tree temperatures. Both forests were even-aged monocultures, which will reduce between-tree temperature variation as compared to more complex natural vegetation types (McCaughey and Saxton, 1988) and the calculated temperatures for the single sample trees in each forest were therefore assumed to be representative for the whole stand.

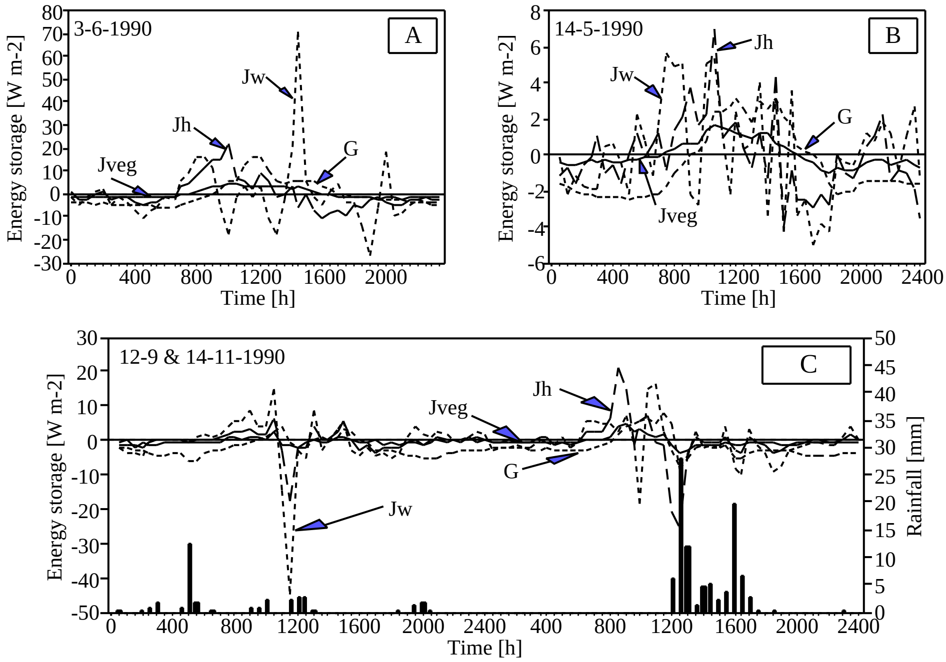


Figure 7.9: *Diurnal patterns of J_h, J_w, J_{veg} and G for selected days with clear sky (A), overcast sky (B), and rainy conditions (C) in Tulasewa forest.*

Finally, energy storage occurs in the soil through changes of its temperature. The spatial variation in soil heat flux (G) was assumed small as the radiative inputs to the soil surface were relatively low due to interception of the light by the forest canopy (Figure 7.6), the undergrowth and the litter layer. As such averages provided by the two soil heat flux plates were assumed to be representative for the whole stand.

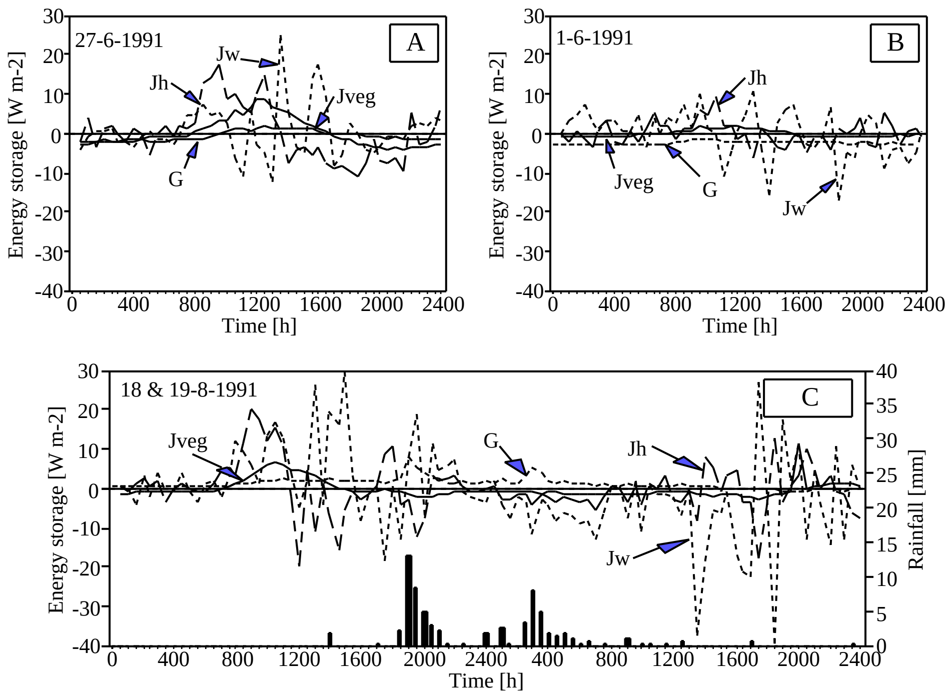


Figure 7.10: *Diurnal patterns of J_h, J_w, J_{veg} and G for days with clear sky (A), overcast sky (B), and rainy conditions (C) in Koromani forest.*

The storage terms were calculated for each 30-minute interval during the respective dry season measurement campaigns. Typical examples of the diurnal patterns of J_h, J_w, J_{veg} and G in Tulasewa and Koromani forests under various climatic conditions are shown in Figures 7.9 and 7.10. On dry days J_h, J_{veg} and G showed distinct diurnal patterns, with energy going into storage (positive values) in the morning and early afternoon, followed by a release of energy (negative values) in the late afternoon and night (Figures 7.9A and 7.10A). The cooling effect of rainfall caused the release of energy, resulting in negative values of J_h, J_{veg} and G. Unlike the other storage terms, J_w did not show a distinct diurnal pattern and under such conditions (Figures 7.9C and 7.10C) fluctuated considerably during daytime with periods of energy going into latent heat storage often being followed by periods of energy release.

Fluxes of J_h, J_{veg} and G were invariably low, remaining within the range -10 to 20 W m^{-2}, whereas the variation of J_w was much larger with extremes ranging from -50 W m^{-2} to 70 W m^{-2} (Figures 7.9 and 7.10). The soil heat flux at Tulasewa forest reached values of up to 20 W m^{-2} on sunny days, whereas that at Koromani forest was in the range of -6 to 7 W m^{-2}. Total daytime energy storage was generally less than 3% of R_n on dry days. On rainy days, however, the total daytime storage could exceed 10% of R_n, and should therefore not be neglected. The storage terms may thus safely be neglected on dry days but should be taken into account around sunrise and sunset as well as during rainy periods.

7.6 Sensible and Latent Heat Fluxes

7.6.1 The Temperature Fluctuation and Bowen Ratio Energy Balance Methods

One of the conventional methods to determine the sensible and latent heat fluxes H and λE is the Bowen Ratio Energy Balance method (Angus and Watts, 1984). The Bowen ratio (β) is defined as the ratio of the sensible heat flux to the latent heat flux (Thom, 1975):

$$\beta = \frac{H}{\lambda E} \tag{7.18}$$

When both the available energy A (Equation 7.7) and β are known, the magnitudes of H and λE can be determined from Equations 7.19 and 7.20, respectively.

$$H = \frac{A}{1 + \beta^{-1}} \tag{7.19}$$

$$\lambda E = \frac{A}{1 + \beta} \tag{7.20}$$

The exchanges of sensible and latent heat are turbulent transfer processes which, in the absence of advection and under steady conditions, may be described by (Thom, 1975):

$$H = -\rho c_p \cdot K_H \frac{\partial T}{\partial z} \tag{7.21}$$

$$\lambda E = -\rho c_p \cdot K_E \frac{\partial q}{\partial z} \tag{7.22}$$

where K_H and K_E are eddy diffusivity coefficients for heat and vapour respectively (Thom, 1975). The exact magnitudes of these coefficients are generally unknown and depend on the stability conditions of the atmosphere. K_H may be assumed equal to K_E (Monin and Yaglom, 1971) and as ∂T and ∂q may be approximated by the finite difference of measurements made at two levels within a layer of constant flux above a homogeneous forest canopy, the Bowen ratio becomes (Jarvis *et al.*, 1976):

$$\beta = \frac{c_p}{\lambda} \cdot \frac{T_2 - T_1 + \Gamma \cdot (z_2 - z_1)}{q_2 - q_1} \tag{7.23}$$

The gradients of T and q are generally small above forest canopies, which places heavy demands on the quality of the instruments used for their measurement, especially when these measurements need to be made over longer periods of time.

As an alternative, β may be obtained from standard deviations and correlation coefficients of dry- and wet-bulb temperatures, as measured with fast-response thermocouples at a single level above the canopy (Vugts *et al.*, 1993). With this method the need for expensive equipment for gradient measurements and time consuming calibrations is eliminated. Vugts *et al.* (1993) found good agreement between fluxes of H and λE as determined on the one hand from Bowen ratios based on measured gradients of T and q and values of β obtained with the correlation method for a two-day period in Tulasewa forest. However, due to problems with the supply of moisture to the wick of the wet-bulb thermocouple sensor the correlation method could be used for the calculation of β for short periods of time (several days) only. The method will therefore not be discussed further, and the reader is referred to the publication by Vugts *et al.* (1993) for more details. Improvements of the wet-bulb sensors are presently being made and tested at FES-VUA, and the usefulness of this promising method depends on whether reliable wet-bulb temperature measurements can be made in future.

Arguably, the best way to determine H and λE is the eddy correlation technique (Shuttleworth *et al.*, 1984), but the costs and delicacy of the instruments (sonic anemometers) are likely to prohibit the day-to-day application of this method in undeveloped tropical countries.

7.6.2 Application of the Temperature Fluctuation and Bowen Ratio Energy Balance Methods

A cheap and reliable alternative to determine H is the temperature fluctuation method (Tillman, 1972; De Bruin, 1982; Lloyd *et al.*, 1991; Vugts *et al.*, 1993; De Bruin *et al.*, 1993). When R_n and energy storage components are also measured, λE may be deduced from the energy balance equation (Equation 7.7) and it is thus referred to as the TFEB method. Turbulent motions of the air near the vegetation canopy are responsible for most of the vertical transfer of heat (Thom, 1975). The standard deviation of the temperature (σ_T, obtained from high frequency measurements of temperature with fast-response thermocouples) may serve as a measure of the intensity of temperature fluctuations caused by turbulence, and is therefore related to H with the term $\frac{\partial T}{\partial z}$ in Equation 7.21 effectively being replaced by $\frac{\sigma_T}{z}$. Tillman (1972) obtained the following expression relating T and σ_T to H under unstable atmospheric conditions ($Ri < -0.05$), where z is replaced by $z - d$ to account for tall vegetation and h_σ is a constant equal to 0.7 (Wijngaard and Cote, 1971):

$$H = h_\sigma \rho c_p \sqrt{(z-d)\frac{g}{T}} \cdot \sigma_T^{1.5} \tag{7.24}$$

Although the formula was developed for application during unstable conditions ($Ri < -0.5$), Frumau (1993) showed that the error in H remained less than 10% if the formula was applied to situations with $-0.5 < Ri < -0.1$ at Tulasewa forest. At near-neutral atmospheric stability ($Ri \approx 0$) errors in H of up to 65% were observed when equation 7.24 was used (Frumau, 1993). However, as H and λE are generally small under such conditions the error in the daily ET total as a result of the error in H remains low. Errors in H resulting from uncertainties in d may be minimized by measuring T and σ_T at sufficient height above the forest canopy (Vugts *et al.*, 1993).

The TFEB method seems to be less sensitive to inhomogeneities in the terrain and vegetation than the BREB method, and has the additional advantage that calibration errors are avoided by measuring at a single level. However, the method cannot be used under stable atmospheric conditions and, if the thermocouples are not shielded, neither during periods of rainfall.

Vugts *et al.* (1993) and Frumau (1993) compared estimates of H and λE as obtained with the **TFEB** method over a two-day period at Tulasewa forest with those obtained with the **BREB** method. Both methods gave comparable results with differences generally being less than 10%. A similar exercise on the data collected at Tulasewa and Koromani forests is presented below, using much larger data sets. The Bowen ratio was calculated for 30-minute intervals over a period of 30 (Tulasewa

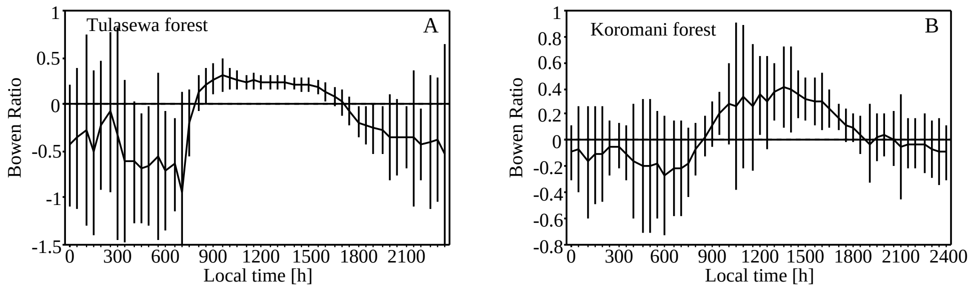


Figure 7.11: *Average diurnal course of β at (A) the Tulasewa (n= 30) and (B) the Koromani forest (n= 34) sites. Standard deviations of the means represented by vertical bars.*

forest) to 34 (Koromani forest) dry days with varying soil moisture deficits. At both forests β was calculated from temperature and humidity data collected at the highest (z_3) and lowest (z_1) levels with the calibrated Rotronic sensors. Half-hourly periods for which the wind direction was such that the fetch was insufficient (Section 7.3.3) were excluded. Estimates of H were obtained from β and the corresponding available energy A using Equation 7.19. The average diurnal patterns of β for each of the forest sites are shown in Figure 7.11 A and B. The Bowen ratio was usually negative at night reaching minimum values of -0.7±0.64 and -0.3±0.46 just before sunrise in Tulasewa and Koromani forests, respectively. After sunrise, β increased sharply to a maximum of 0.3±0.2 in the early morning (9:00–10:00 h) in Tulasewa forest, after which a gradual decrease occurred towards negative values in the late afternoon (18:00 h). The diurnal course of β at Koromani forest differed in that higher daytime values and a maximum of 0.4±0.3 in the early afternoon rather than in the morning. The higher β values observed for Koromani forest may be caused by its age, and possibly also by the damage afflicted to the canopy by cyclone Sina, which may have reduced the potential of the forest to evaporate to the extent that more energy was available for the sensible heat flux (*cf.* Table 6.8). The calculated values of β were well within the range of 0.1 to 1.5 for dry-canopy daytime values for coniferous forests in the temperate zone given by Jarvis *et al.* (1976).

The TFEB method was used to calculated H for half-hourly intervals with unstable conditions (Ri < -0.01) and wind directions such that the fetch was sufficient. The average diurnal courses of the Richardson number at Tulasewa and Koromani forests for the periods under consideration are shown in Figures 7.12A and 7.12B, respectively. Near-neutral to stable conditions (Ri > -0.01) prevailed during the late afternoon and at night, implying that the TFEB method could not be used to calculate H for these periods. The atmosphere generally turned unstable in the early morning (8:00–9:00 h), with the average Ri reaching minimum values of -0.55(±0.87) at 9:00 h in Tulasewa forest and of -0.22(±0.47) around 10:00 h in Koromani forest. In the early afternoon Ri increased to values of around -0.07 and then remained fairly constant until the late afternoon (17:00 h). As such the use of the TFEB method for the determination of H was generally restricted to daytime conditions (8:00–17:00 h).

The sensible heat fluxes for the periods under consideration were calculated using T and σ_T values measured with the thermocouple at the highest level to minimize the effects of errors in d on H (Frumau, 1993; Vugts *et al.*, 1993). Displacement lengths

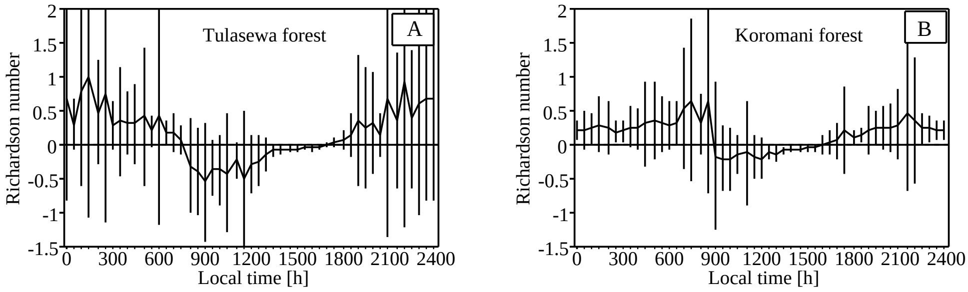


Figure 7.12: *Average diurnal course of the Richardson number at (A) Tulasewa (n= 30) and (B) Koromani forest (n= 34). Standard deviations of the means represented by vertical bars.*

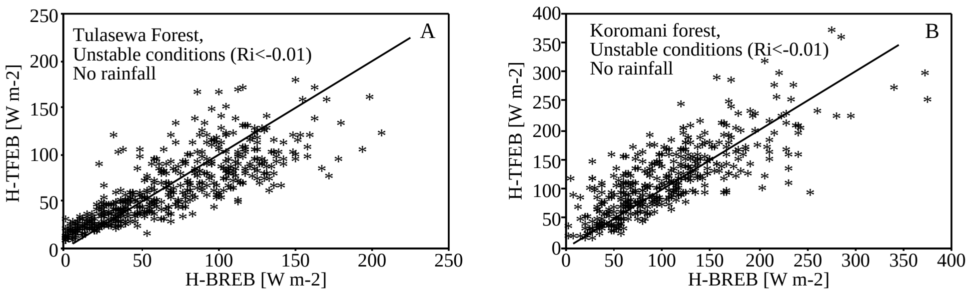


Figure 7.13: *Half-hourly fluxes of sensible heat obtained with the TFEB method* versus *corresponding values obtained with the BREB method for (A) Tulasewa (n= 478) and (B) Koromani (n= 404) forest. The solid line represents equal values.*

of 7.1 m and 10.4 m were used in the calculations for Tulasewa and Koromani forests, respectively (Section 7.3.3). The results of the TFEB method are plotted against those of the BREB method in Figures 7.13A and 7.13B for Tulasewa and Koromani forests, respectively. The methods showed good agreement with no significant differences (α= 0.05) between averages of H, although the average H obtained with the TFEB method was about 8% less than that obtained with the BREB method in Tulasewa forest. On the other hand, the TFEB method overestimated H on average by about 13% at the Koromani forest site.

The agreement between the two methods was less good for the individual half-hourly values as indicated by the large scatter in Figures 7.13A and 7.13B. Some of the scatter will undoubtedly have been caused by errors in H as obtained by the BREB method, because this method is very sensitive to errors in measured gradients of T and q (Angus and Watts, 1984). Measured gradients of T and q were in the ranges of 0.01–0.03 $^{\circ}$C m^{-1} and 2–4$\cdot 10^{-5}$ kg m^{-1}, respectively. The Rotronic sensors were sufficiently accurate for the measurement of the temperature gradients but failed occasionally in the measurement of q (possibly due to the filter surrounding the sensor), resulting in unrealistic values of β, and therefore of H and λE. This is illustrated in

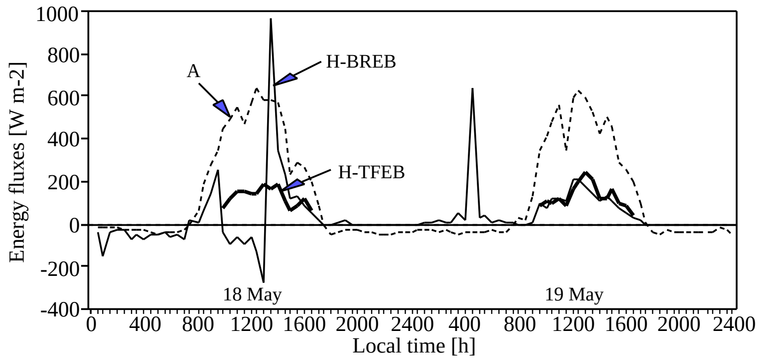


Figure 7.14: *Comparison between fluxes of sensible heat as determined with the BREB and TFEB methods, and available energy on 18–19 May 1991 at the Koromani forest site.*

Figure 7.14 where the sensible heat fluxes over a two-day period at the Koromani forest site are shown. The diurnal courses of the available energy, temperatures and relative humidities were similar on both days, and so were the sensible heat fluxes obtained with the TFEB method. However, the BREB method provided unrealistic values of H during the morning and early afternoon of the first day, whereas both methods compared well on the second day (Figure 7.14).

The standard deviation of temperature is positive by definition and will never be zero due to instrumental noise in the thermocouple – datalogger system. As such the outcome of Equation 7.24 is inherently larger than zero. The influence of instrumental noise on σ_T may be considered negligible if temperature fluctuations (and therefore H) are large, but may cause an overestimation of H if the temperature remains fairly constant ($H \approx 0$ W m^{-2}). In practice a minimum σ_T of 0.05 °C was observed for periods when H-BREB was close to zero. Assuming that the minimum σ_T could be wholly attributed to noise, a minimum offset of about +10 W m^{-2} would be expected. The sensitivity of the TFEB method to errors in d was tested for the Koromani and Tulasewa forest sites using 3121 and 1525 30-minute periods with $Ri < -0.01$, dry conditions and $A > 50$ W m^{-2}. For both data sets a 15% error in d resulted in errors of less than 4% of average values of H and of less than 1.5% in those of λE. As such the use of a constant d, independent of wind direction, to calculate H will not have caused large errors in the determination of λE and is therefore justified.

7.6.3 Penman-Monteith Model

Neither the TFEB method nor the BREB method could provide a continuous time series of H or λE and the Penman-Monteith model (Equation 5.3) was therefore used for the determination of daily evapotranspiration rates throughout the respective observation periods. Application of the model requires knowledge of the surface resistance r_s, which varies both with micro-meteorological and soil moisture conditions (Monteith, 1965; Shuttleworth, 1988). When estimates of λE are available (*e.g.* via the BREB or TFEB methods), the Penman-Monteith formula can be rearranged and used inversely

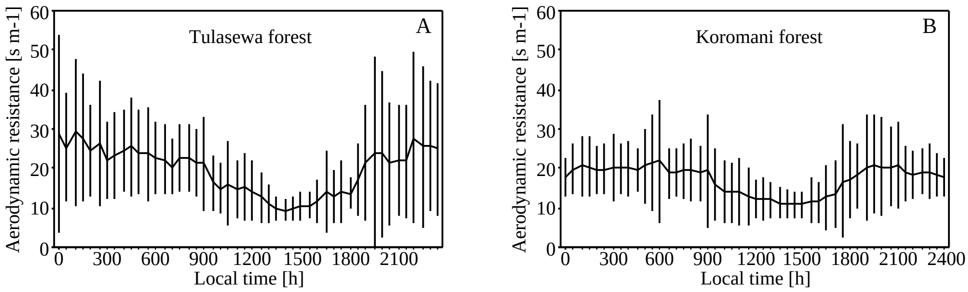


Figure 7.15: *Average diurnal courses of r_a in (A) Tulasewa (n= 31 days) and (B) Koromani (n= 30 days) forests. Standard deviations around the mean are represented by the vertical bars.*

to provide estimates of r_s:

$$r_s = \frac{\rho c_p}{\gamma} \cdot \frac{\delta e}{E} + r_a \cdot \left(\frac{\Delta A}{\gamma E} - \frac{\Delta}{\gamma} - 1 \right) \tag{7.25}$$

where r_a may be obtained from measured wind speeds for known values of z_0 and d (Section 7.3.3) according to Equation 5.4.

Average diurnal patterns of r_a are shown in Figures 7.15A and 7.15B for Tulasewa and Koromani forests, respectively. In spite of the differences in height of the forests the aerodynamic resistances were quite similar, with daytime averages of 14.1($\pm$8.2) s m^{-1} and 13.5($\pm$7.6) s m^{-1} and afternoon minima of 9.4($\pm$2.8) s m^{-1} and 10.7($\pm$3.2) s m^{-1} at Tulasewa and Koromani forests, respectively. The errors in average r_a as a result of errors of 15% in both d and z_0 were less than 23% and 18% in Tulasewa forest and Koromani forests, respectively.

Equation 7.25 was used to calculated r_s for Tulasewa and Koromani forests from estimates of λE, as obtained with the TFEB method, and average diurnal courses of r_s for the two forests are shown in Figures 7.16A and 7.16B, respectively. The surface resistance was high during the night and dropped steeply shortly after sunrise after which it remained low until late in the afternoon. The daytime (8:00-17:00 h) average r_s was 43($\pm$21) s m^{-1} in Tulasewa forest, with a minimum of 35($\pm$11) s m^{-1} in the morning, whereas that in Koromani forest was higher at 113($\pm$126) s m^{-1} with a minimum of 62($\pm$20) s m^{-1}. The sensitivity of the calculated r_s to errors in d and z_0 was low, with errors of 15% in both d and z_0 resulting in errors of less than 3% and 6% in average values of r_s in Tulasewa and Koromani forests, respectively.

Measurements of stomatal resistances with a porometer in the canopy of Koromani forest (Opdam, 1993) indicated that r_{st} followed the diurnal course of r_s, although at higher values. Stomatal resistances above 15000 s cm^{-1} were observed throughout the canopy before sunrise (6:30 h) on July 17, 1991, after which r_{st} dropped sharply to 356($\pm$160) s m^{-1} at 7:20 h and remained fairly constant until about 17:00 h when r_{st} increased again to values wel above 1000 s m^{-1}. There was a distinct decrease in r_{st} with height in the canopy, which was also observed in tropical rainforest in Amazonia by Roberts *et al.* (1990). The daytime average r_{st} in the lower canopy (obtained from 35 measurements on five needle sets at 13 m) amounted to 594($\pm$220) s m^{-1}, and decreased to 512($\pm$225) s m^{-1} at mid canopy level (16 m) and 406($\pm$140) s m^{-1}

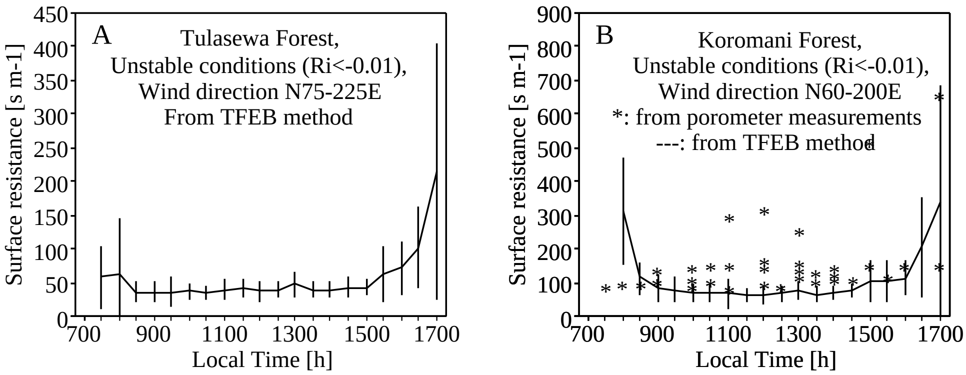


Figure 7.16: *Average diurnal patterns of r_s in (A) Tulasewa (n= 31 days) and (B) Koromani forest (n= 12 days). Estimates of r_s (*) obtained from measurements of r_{st} and LAI (Koromani forest only) added for comparison. Standard deviations around the mean represented by vertical bars.*

near the tree top (19 m). Assuming that the bulk stomatal resistance for the whole canopy could be approximated by the average of the measurements in the upper and middle regions of the crown, where most of the foliage biomass was (*cf.* Roberts *et al.*, 1990), and using a LAI of 3.5 m^2 m^{-2} (Section 11.3.6) an average r_s of 131(±64) s m^{-1} was calculated (see also Section 5.4.4). This is quite comparable to the daytime average obtained with Equation 7.25 from the TFEB method (Figure 7.16B). The good agreement between the two methods for the determination of r_s suggests that the combination of porometer measurements of r_{st} and measurements of the LAI with a ceptometer may provide a good indication of the surface resistance of forests located in terrain that is not suited to the use of micro-meteorological methods.

We were not able to find any information on r_s or r_{st} of other tropical pine plantations for comparison with the values presented above. However, in Japan, Sugita (1987) calculated the surface resistance of a 10–13 m high *Pinus densiflora* forest from a combination of eddy correlation measurements and the Penman-Monteith model and obtained monthly daytime averages ranging from 40 and 120 s m^{-1} over the period of a year. Jarvis *et al.* (1976) provided a list of minimum r_{st} values for coniferous forests in the temperate zone, with r_{st} ranging from 120 to 950 s m^{-1} for current year needles, whereas values up to 2700 s m^{-1} were measured in old growth. This suggested that the values presently found for r_s and r_{st} were within the normal range for (temperate) coniferous forests.

To allow the inclusion of the effect of variations in soil moisture deficit (SMD) on r_s, in addition to those in micro-meteorological conditions, values of SMD were derived for the upper 1 m of soil. Firstly field capacity conditions (drainage just stopped) were assumed whenever soil moisture tensions reached a value of pF= 2.0. Measurements of volumetric moisture content (θ) were converted to soil water tension via the soil moisture retention curves given in Appendix 25. Discontinuous time series of soil moisture deficits could then be calculated for the Tulasewa and Koromani forest plots by substracting actual moisture content, as measured with the capacitance probe, from the moisture content at field capacity. A total of 20 days were selected with SMDs ranging from zero to 115 mm for Tulasewa forest (SMD_{max}= 208 mm, Section 4.3.4) and 13 days with SMDs ranging from 0 to 46 mm for Koromani forest (SMD_{max}= 136 mm). The data sets were divided so as to conform to the following conditions:

- Unstable atmospheric conditions (Ri < -0.01)
- No rainfall
- Wind direction such that the fetch was sufficient

For illustrative purposes graphs of r_s against the available energy A, vapour pressure deficit VPD, SMD, wind speed u and temperature T measured at 32.1 m above Koromani forest are shown in Figures 7.17A–E, respectively. Corresponding graphs for Tulasewa forest were similar and are not shown. Figure 7.17A indicates that separate expressions were necessary for the modelling of r_s during daytime (a gradual decreases with increasing A) and during the early morning and late afternoon (sharp increase with decreasing A). Separate data sets were compiled for daytime conditions and early morning – late afternoon conditions. Daytime periods represented data collected between 8:00 h and 17:00 h, with A > 200 W m^{-2} at Tulasewa forest and A > 120 W m^{-2} at Koromani forest. Multiple linear regression techniques were used to relate r_s (in s m^{-1}) to A (W m^{-2}), VPD, (mbar), SMD (mm), u (m s^{-1}) and T (°C) (*cf.* Shuttleworth, 1988). The following expression was found for r_s in Tulasewa forest for early morning – late afternoon periods:

$$r_s = 677 - 3.46A + 11.07VPD - 44.71SMD \qquad \text{n}= 35,\ r^2 = 0.64 \tag{7.26}$$

where most of the variation was explained by the available energy (r^2 = 0.61) while the inclusion of VPD and SMD increased the coefficient of determination to 0.64. The inclusion of T and u did not improve the regression significantly (r^2 = 0.66) and these were therefore not included. Daytime r_s may be calculated from the equation:

$$r_s = 28.9 - 0.068A - 4.27VPD - 0.11SMD \qquad \text{n}= 215,\ r^2 = 0.58 \tag{7.27}$$

where A and VPD explained 52% of the variation in r_s, whereas inclusion of SMD increased the coefficient of determination to 0.58. Inclusion of T and u again did not improve the fit significantly, increasing the r^2 to 0.60.

Similarly, the early morning – late afternoon expression found for Koromani was:

$$r_s = 850 - 5.48A + 60.2VPD - 6.9u - 23.6T \qquad \text{n}= 35,\ r^2 = 0.53 \tag{7.28}$$

where A explained 21% of the variation in r_s. Inclusion of VPD, u and T in the regression increased the coefficients of determinations to 0.50, 0.51 and 0.53, respectively. The daytime expression obtained from the Koromani data was:

$$r_s = -87.6 - 0.21A + 5.0VPD - 2.9u + 8.5T \qquad \text{n}= 183,\ r^2 = 0.59 \tag{7.29}$$

where 22% of the variation in r_s was explained by A. Inclusion of VPD, u and T increased the coefficients of determinations to 0.49, 0.54 and 0.59, respectively. Unlike

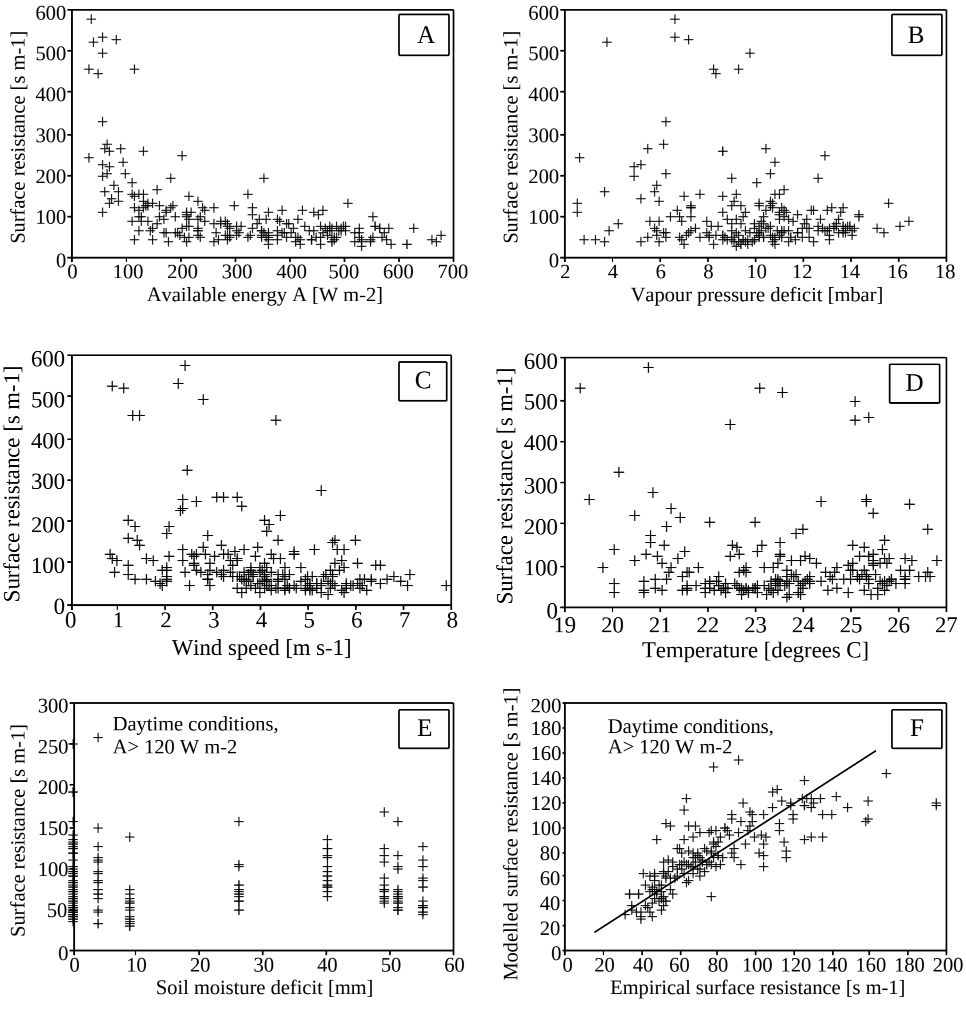


Figure 7.17: *Surface resistance* r_s versus *available energy A (A), vapour pressure deficit (B), wind speed (C), temperature (D) and soil moisture deficit (E) for Koromani forest. Figure F shows empirical values of* r_s*, as derived from the TFEB method, against values obtained with the regression models.*

the situation at Tulasewa inclusion of SMD did not increase the coefficient of determination in Koromani forest. A plot of the r_s values calculated with Equation 7.29 against empirically derived values data (TFEB method plus Equation 7.25) in Koromani forest has been added to Figure 7.17F to illustrate the scatter associated with the use of the above expressions.

Daily values for SMD were required for the calculation of r_s with Equations 7.26 and 7.27 for Tulasewa forest. Since daily soil moisture measurements were not made estimates of SMD for the upper metre of the soil were derived with a model based on a similar model described by Calder *et al.* (1983) . The model required daily rainfall totals (P) and estimates of the Penman open water evaporation (Penman, 1948; Appendix 22.2) as inputs to solve a soil water balance for SMD at a daily time step. When the soil is at or drier than field capacity ($SMD > 0$ mm) drainage was assumed negligible and the change in SMD was described by the following equation:

$$SMD_{i+1} = SMD_i - P + f_i \cdot E_0 \tag{7.30}$$

where i is the day number. When moisture content exceeded field capacity ($SMD <$ 0 mm), Equation 7.30 was modified to simulate drainage according to:

$$SMD_{i+1} = 0.5SMD_i - P + f_i \cdot E_0 \tag{7.31}$$

The factor f_i was introduced to allow for the extraction of moisture by tree roots from depths below the upper metre of the soil. Its value decreased with increasing SMD because the fraction of moisture extracted from the upper metre of soil is likely to decrease with increasing deficits in this layer. As such the following classes were used for the estimate of f_i:

- If SMD_i <0 mm: f_i= 1.0
- If 0< SMD_i <50 mm: f_i= 0.65
- If 50< SMD_i <80 mm: f_i= 0.50
- If 80< SMD_i < SMD_{max} mm: f_i= 0.35
- If SMD_i > SMD_{max} mm: f_i= 0.0

The modelled SMDs matched those derived from soil moisture measurements for the period July – November 1990 rather well (Figure 7.18), with the difference between the two means of 9%. The fit was less good for the period May – June 1990 when the model overestimated mean SMD by 94%. However, the errors did not result in large changes in the calculated r_s as r_s depended mainly on A and VPD. The use of other criteria for f_i did not improve the fit very much.

Half-hourly values of r_s were calculated from Equations 7.26–7.29 and inserted into the Penman-Monteith equation to obtain continuous time series of λE values for Tulasewa (n= 347 days) and Koromani (n= 140 days) forests. The surface resistance was set to zero during periods with rainfall following the stop–go principle (Calder *et al.*, 1986). Examples of the diurnal variation in λE (Penman-Monteith equation as well as TFEB method), H ($A - \lambda$E from Penman-Monteith equation) and A for different weather conditions are shown in Figures 7.19A–C and 7.20A–C for Tulasewa and Koromani forests, respectively. The diurnal patterns of the energy and storage terms on these days have been presented earlier (Figures 7.9 and 7.10). The average daytime

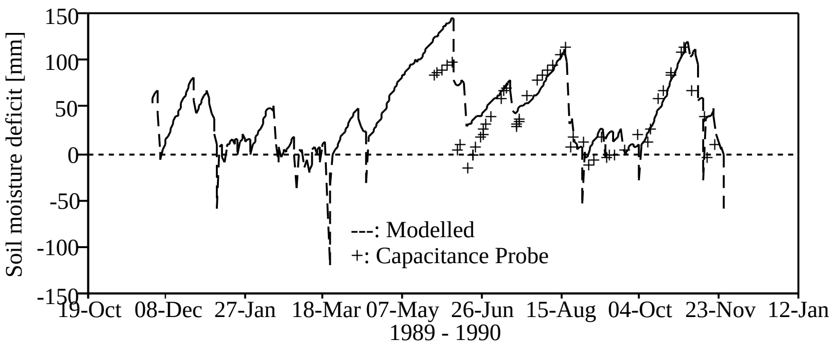


Figure 7.18: *Measured and modelled soil moisture deficits in Tulasewa forest.*

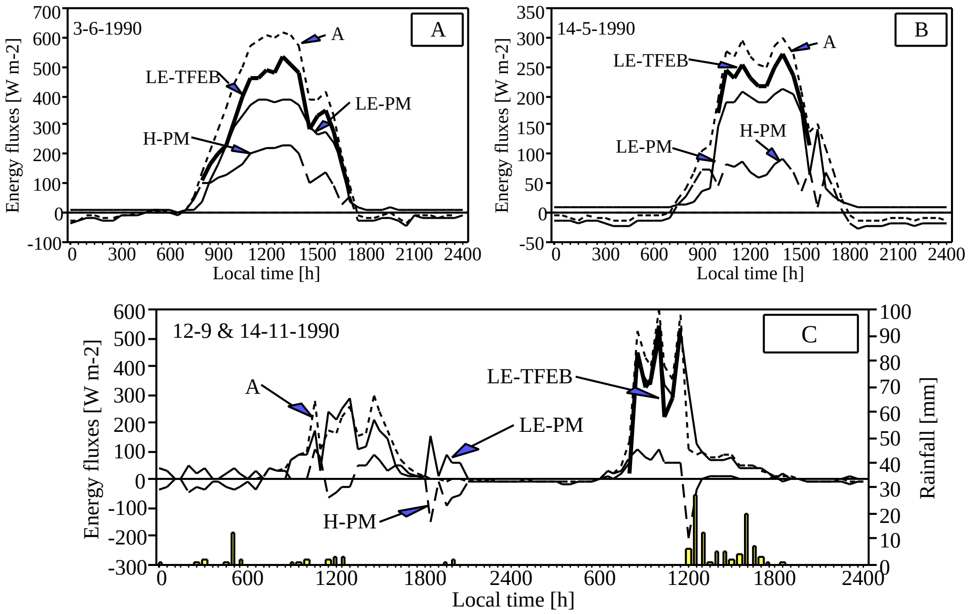


Figure 7.19: *Diurnal patterns of the latent heat flux (LE-PM, LE-TFEB only shown for dry periods with $Ri < -0.01$), sensible heat flux (H-PM) and available energy (A) on selected (A) clear, (B) overcast, and (C) rainy days for Tulasewa forest.*

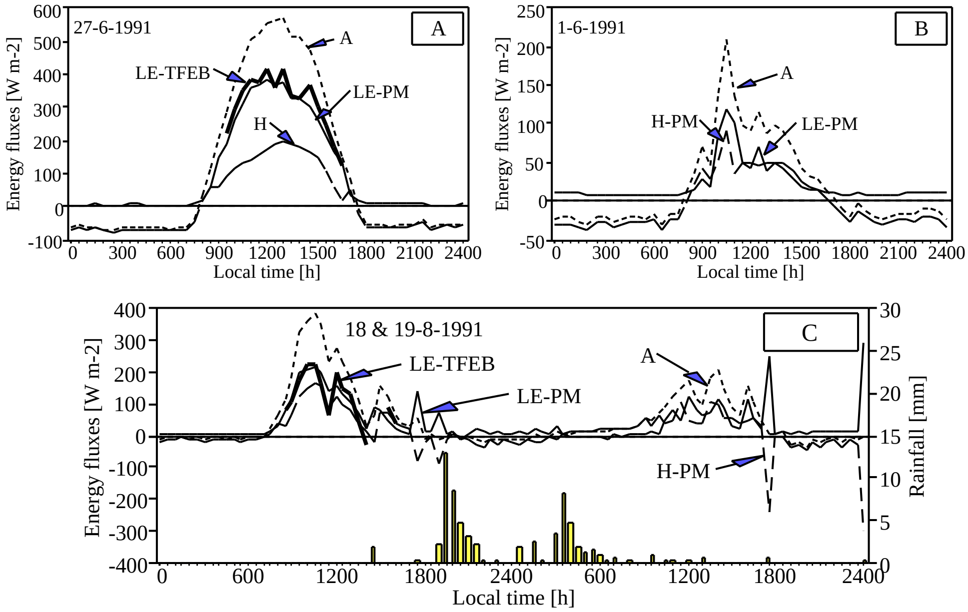


Figure 7.20: *Diurnal patterns of the latent heat flux (LE-PM, LE-TFEB only shown for dry periods with Ri < -0.01), sensible heat flux (H-PM) and available energy (A) on selected (A) clear, (B) overcast, and (C) rainy days for Koromani forest.*

(8:00–17:00 h) wind directions on the selected sunny and overcast days deviated less than 20° from the SE, whereas those on the selected rainy days averaged N138°E and N157°E for Tulasewa forest, and N160°E and N171°E for Koromani forest. Half-hourly estimates of the latent heat fluxes, as calculated with the Penman-Monteith equation, were some 20% lower than those obtained with the TFEB method for both the selected sunny and overcast days at Tulasewa forest, indicating that r_s, as determined from the expressions given earlier, was overestimated for these days. However, much better agreement between the results of the two methods were observed for most other days in the data set (not shown here), as well as for the rainy day. Latent heat fluxes derived with the two different methods also compared well at Koromani forest with differences of less than 10%.

7.7 Summary of Forest Evapotranspiration

Hourly rates of λE in the Tulasewa and Koromani forests, as determined with the Penman-Monteith equation (ET$_{pm}$) for both dry and rainy (P> 0.8 mm h^{-1}) periods, are given in Table 7.6 for Tulasewa and Koromani forests. The highest rates of ET$_{pm}$ occurred around noon (11:30–12:30 h) and averaged 0.68($\pm$0.25) mm h^{-1} (n= 987) and 0.47($\pm$0.22) mm h^{-1} (n= 402) at Tulasewa and Koromani forests, respectively. Nighttime rates of ET$_{pm}$ under dry conditions were low due to the high r_s and averaged 0.01 mm h^{-1} in both forests. Surprisingly, average hourly rates of ET$_{pm}$ during

Table 7.6: *Averages of ET_{pm}, A and R (rainfall rate), and values of $\bar{E}/\bar{R}$ during periods with rainfall, at Tulasewa and Koromani forests. The number of 30-minute periods is represented by n, standard deviations between parenthesis.*

Location, period & data set	**ETpm** [mm h-1]	**A** [W m-2]	**R** [mm h-1]	**E/R**	**n**
Tulasewa forest, Nov '89 - Nov '90, Dry conditions					
Wet season, (8:00-17:00 h)	0.57 (0.28)	474 (226)			2495
Dry season (8:00-17:00 h)	0.44 (0.25)	381 (210)			3576
Wet & dry season (8:00-17:00 h)	0.50 (0.27)	420 (222)			6071
Tulasewa forest, Nov '89 - Nov '90, During rainfall					
Wet & dry season	0.18 (0.25)		5.0 (7.2)	0.04	768
Wet & dry season (8:00-17:00 h)	0.28 (0.28)	119 (124)	6.0 (8.6)	0.05	387
Dry season (8:00-17:00 h)	0.30 (0.30)	120 (131)	3.6 (5.0)	0.08	135
Koromani forest, Apr '91 - Sep '91, Dry conditions					
Dry season (8:00-17:00 h)	0.30 (0.20)	321 (184)			2550
Koromani forest, Apr '91 - Sep '91, During rainfall					
Dry season	0.08 (0.12)		4.2 (6.2)	0.02	143
Dry season (8:00-17:00 h)	0.13 (0.15)	96 (71)	4.6 (6.6)	0.03	68

rainfall were lower than those for dry conditions in spite of zero surface resistance (Calder, 1979). This must be due to the low amounts of (measured) available energy during those conditions (Table 7.6) and the high relative humidity. Corresponding average rainfall rates were calculated to enable the calculation of $\bar{E}/\bar{R}$ for comparison with the $\bar{E}/\bar{R}$ values obtained with the Gash analytical model of rainfall interception (Section 6.4.1). A discussion of the differences in evaporation from a wet canopy obtained with the two methods has been given earlier in Section 6.4.1.

The mean daily ET_{pm} at Tulasewa forest amounted to 4.85(±1.56) mm day^{-1} over a 347-day period between November 30, 1989, and November 27, 1990. The Penman open water evaporation for the corresponding period was 4.61(±1.55) mm day^{-1}, resulting in an ET_{pm}/E_0 ratio of 1.05. The total annual ET_{pm} (November 1989–1990) amounted to 1770 mm, with corresponding totals of E_0 and P of 1672 mm and 1964 mm, respectively. The annual variations in ET_{pm} and E_0 for Tulasewa are shown in Figure 7.21.

ET_{pm} was high during the wet season (November – April), averaging 5.41(±1.52) mm day^{-1} (n= 170). The dry season ET_{pm} (May–November) was lower with an average of 4.32(±1.40) mm day^{-1} (n= 177). This was mainly due to low radiation inputs (table 7.6), rather than to moisture shortages as the dry season of 1990 was relatively wet (table 6.2). Corresponding E_0 values were 5.24(±1.51) and 3.96(±1.34) mm day^{-1}, respectively. The ratio of ET_{pm} to E_0 was usually higher than 1.0, but dropped to 0.7–0.8 during dry periods of several weeks, to be followed by a sharp increase after soil moisture levels were replenished by rainfall (Figure 7.21). A summary of the rates of ET_{pm}, although taken over slightly different periods, will be provided in Table 9.2 in Chapter 9.

The dry season average ET_{pm} at Koromani forest amounted to 2.96(±1.12) mm day^{-1}

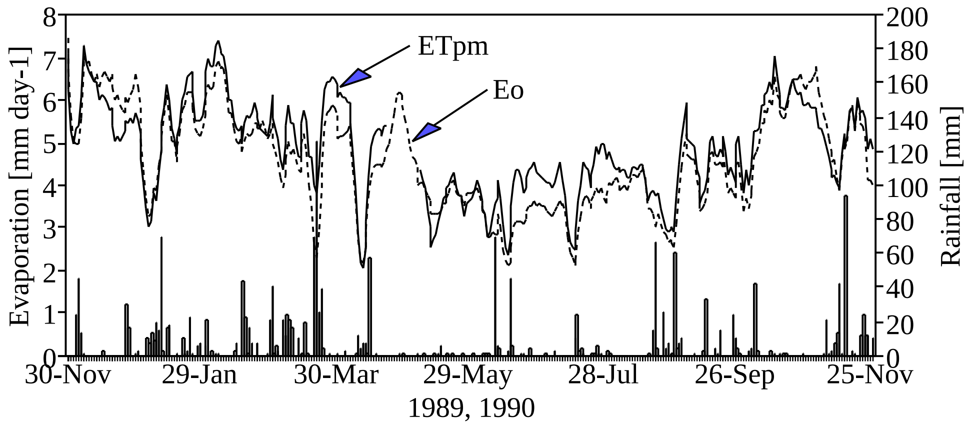


Figure 7.21: *Daily rainfall totals and annual patterns of* E_0 *and* ET_{pm} *(5-day moving averages) at Tulasewa forest from November 30, 1989, until November 27, 1990.*

(n= 140), and was much lower than that obtained for the corresponding period a year earlier at Tulasewa forest (3.96(±1.13) mm day^{-1}; n= 135), in spite of a higher average E_0 in 1991 (4.31(±0.96) *versus* 3.63(±1.00) mm day^{-1}). The variations in ET_{pm} and E_0 during the dry season of 1991 at Koromani forest are shown in Figure 7.22.

Total dry season ET_{pm} at Koromani forest amounted to 424 mm (1991) *versus* 573 mm for the same period a year earlier at Tulasewa forest, with corresponding rainfall totals of 321 mm and 467 mm, and E_0 totals of 616 mm and 519 mm (see also Table 9.2, but note the differences in period lenghts). The higher rainfall during the 1990 dry season at Tulasewa cannot be the main reason for its higher evapotranspiration as no water stress was observed in 1991 at Koromani forest (Section 6.5). Rather, the difference in ET_{pm} between the two forests relate to differences in age, and therefore growth rates (Schulze and George, 1987). Furthermore, as stated repeatedly, the canopy of Koromani forest was severely damaged during the passage of cyclone Sina in November 1990, and the foliage biomass had not yet returned to pre-cyclone levels.

The errors in ET totals (computed with the Penman-Monteith equation) as a result of errors in surface roughness parameters were small, with errors in average ET_{pm} values resulting from errors of 15% in d and z_0 and 6% in r_s being lower than 2% and 4% in Tulasewa and Koromani forests, respectively. Errors in R_n or A were thought to be lower than 5%. As such the total error in ET_{pm} values for both forests is probably lower than 10%. The errors associated with daily and half-hourly values may be higher due to uncertainties in the estimation of soil moisture deficit, and therefore r_s.

The ET values derived in this chapter for the two study forests will be compared with estimates of ET in grassland (Chapter 5) in Chapter 9.

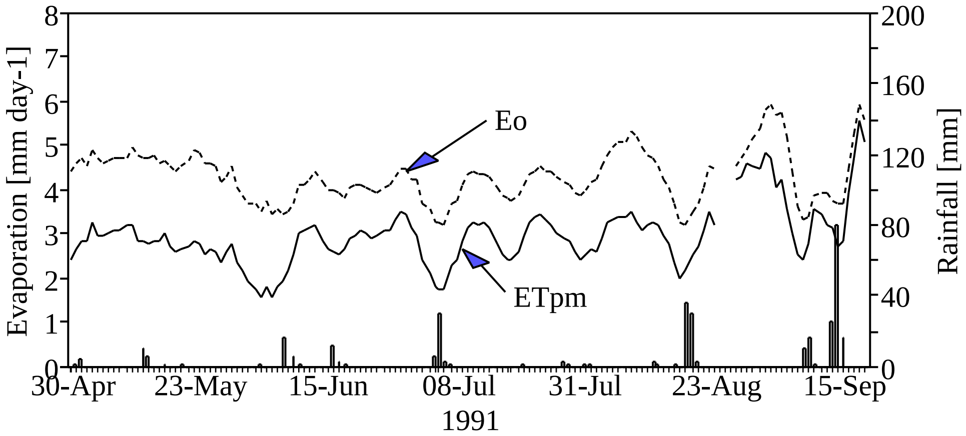


Figure 7.22: *Daily rainfall totals and E_0 and ET_{pm} patterns (5-day moving average) at Koromani forest from April 30 until September 19, 1991.*

Chapter 8

Water Use of the Oleolega Forest

8.1 Introduction

In the previous chapters estimates for the average daily water use of grassland and pine forest have been obtained from a combination of soil moisture depletion, rainfall interception and micro-meteorological measurements. These estimates were obtained for small forest plots in relatively flat terrain, and may not accurately reflect ET rates from steeply dissected terrain covered with patches of pine forest, native forest and grass. The latter situation is far more common in Fiji and an integrated estimate of the overall evaporation rate for this kind of terrain can only be obtained through the quantification of a catchment water balance. Furthermore, ecosystem nutrient exports are generally strongly correlated with streamflow outputs (Likens *et al.*, 1977) whereas the best estimates of nutrient inputs to the system via weathering may be obtained by the catchment nutrient budget technique (Clayton, 1979; Bruijnzeel, 1983a). In this context the following objectives were formulated for the hydrological study in the forested Olelolega catchment:

- To provide baseline information on the water use of mature pine forest, against which the impact of harvesting and subsequent burning on water yield can be assessed
- To allow the calculation of nutrient exports from forested catchment, both for comparison with losses estimated for the respective research plots, and for the assessment of the impacts of harvesting and burning on the water quality *c.q.* nutrient losses
- To evaluate the average annual contribution of rock weathering to the overall pine forest nutrient budget

In this chapter the water budget will be presented for the 63 ha Oleolega catchment (Figure 3.4) which had been planted to pine in 1975, whereas hydrochemical aspects of the catchment in the forested state will be presented in Chapters 13 and 14. Details on the impact of harvesting and subsequent burning of the slash on water yield and quality will be discussed in Chapter 15. A preliminary water budget for the catchment in the forested state based on the data collected in 1990 was published by Schellekens (1992). However, this budget was slightly in error as a preliminary streamflow rating curve was used, which tended to overestimate peakflows. The corrected water budget is presented in Section 8.3.

8.2 Methods and Instrumentation

Hourly rainfall data were collected from January 4, 1990 onwards with a SIAP UM-8100 pluviograph (orifice at 1.5 m) located near the outlet of the catchment (116 m a.s.l). To obtain an areal estimate of rainfall over the drainage basin two custom-made gauges (OP1, next to the pluviograph; OP5, at the top of the catchment at 245 m a.s.l., orifices at 0.4 m) and a standard rain gauge (OP4, located near sample point 22 at 170 m a.s.l., orifice at 1.0 m) were positioned along the catchment boundary (see Figure 15.3 for locations) between January and March 1990. The mean areal precipitation was estimated using the Thiessen polygons method (Ward and Robinson, 1990) dividing the drainage basin into three parts with 35% of the total area assigned to the pluviograph and gauge OP1, 53% to gauge OP4 and 11% to gauge OP5 (Schellekens, 1992). Topographical aspects were not taken into consideration, in view of the small size of the catchment. The gauges were emptied at least once a week and measurements continued until April 4, 1992. A separate rain gauge (OP2, orifice at 60 cm), similar to those described in Section 6.2, was used to collect rain water for chemical analysis. This gauge was located near the outlet until December, 1990, after which it was moved to the top of the catchment to avoid contamination of samples by logging activities (*e.g.* dust). A total of 23 rain water samples were collected until October 1991.

The water level (H) of the Oleolega creek was measured continuously from January 4, 1990, until April 4, 1992, with an automatic recorder (Leupold & Stevens F4) placed 2.5 m upstream from a culvert. A fixed staff gauge was used as a reference. The approach channel to the culvert was straight. The culvert consisted of four 1.4 m sections of cylindrical concrete (0.91 m diameter) with a slope of 0° at the upstream end, and 2.5° at the downstream end. It had been built on solid rock and leakage underneath the structure could safely be neglected. Both the upstream and downstream walls of the culvert were covered with cement to avoid leakage through the structure. A low V-shaped concrete hump at the joint between the first and the second section of the culvert enabled accurate water level measurements to be made at low discharges. Flood marks indicated that the culvert had been flooded in the past, but this did not occur during the present study.

The waterlevel recorder was serviced once a week. However, when logging started in the area after the forest had been wrecked by cyclone Sina the frequency was increased to twice a week until October 1991, thereby improving the time resolution of the measurements. All charts were digitized at FES–VUA. The water level measurements (H, read to the nearest mm) were converted to discharge (Q, in l s^{-1}) via a stage – discharge relation ship developed for the gauging structure. Regression equations were fitted through 100 simultaneous measurements of Q and H over a range of discharges (Q= 0.6–726 l s^{-1}). Discharge was measured volumetrically at low discharges ($Q < 8.3$ l s^{-1}), with the salt dilution method (Gregory and Walling, 1973) at intermediate discharges (Q= 4.1–34 l s^{-1}) and with the velocity area technique (Ott current meter; Gregory and Walling, 1973) at high discharges (Q= 6.8–726 l s^{-1}). The following stage–discharge regression equations were calculated (Van Well, 1993b):

$$Q = 0.07274 \cdot \mathrm{H}^{2.2943}$$
$$\mathrm{n}{=}\ 99,\ r^2 = 0.99,\ \mathrm{H} \leq 16\ \mathrm{cm} \tag{8.1}$$

$$Q = 0.0296 \cdot \mathrm{H}^{2.6810-0.0039 \cdot \mathrm{H}}$$
$$\mathrm{n}{=}\ 100,\ r^2 = 1.00,\ \mathrm{H} > 16\ \mathrm{cm} \tag{8.2}$$

During the study water level reached values outside the range of the rating curve (2–70 cm) on three occasions, for a total duration of 8.5 hours. As the discharges for these events were calculated by extrapolation of Equation 8.2 a small error may have been introduced.

Due to maintenance work on the culvert water levels were not measured correctly between January 22 and March 8, 1990. Discharges for this period were simulated using a runoff simulation model developed by Schellekens (1992) for the Oleolega catchment in the forested state. The simulated streamflow total for the whole of 1990, excluding two excessively wet cyclone periods, was within 6% of the measured total (Schellekens, 1992; Van Well, 1993b). Therefore the error in the estimate of total water use by the forest in 1990 introduced by using model predictions for the two weeks during which data were missing can be considered small.

8.3 Catchment Water Balance

To obtain an estimate for the annual ET from the Oleolega catchment the various components of the water balance need to be quantified. The catchment water balance equation reads:

$$P_a = Q + ET + \Delta G + \Delta S + L \tag{8.3}$$

where P_a is the mean areal precipitation, L represents leakage into or out of the catchment, and ΔS and ΔG represent changes in the soil moisture and groundwater storages, respectively (Ward and Robinson, 1989). All amounts are expressed in mm water depth. The accumulated error in ET obtained from such water balance calculations may easily be as large as 20% (Lee, 1970) due to errors in ΔG and ΔS. However, these may be minimized by a careful selection of the period for which the balance is calculated, and the estimates presented below are thought to have an error of less than 10%. Similarly, over- or underestimates of ET because of ungauged amounts of water leaving or entering the catchment via subterraneous pathways can be minimized by selecting a catchment that is watertight. On the basis of the massive character of the bedrock and the very low hydraulic conductivity of the subsoil (Chapter 4.3.3) L was assumed negligible in the present case.

To obtain estimates of ΔG, master baseflow recession curves were calculated for the dry and wet seasons by fitting Equation 8.4 to observed discharges during selected 17–18 day periods of uninterrupted baseflow.

$$Q_t = Q_1 \cdot K_1^t + (Q_2 - Q_1) \cdot K_2^t \tag{8.4}$$

This equation describes the baseflow recession using two so-called linear reservoirs superimposed on each other (Hall, 1968), where Q_t is the discharge (mm h^{-1} at time t in days), Q_1, Q_2, K_1 and K_2 are the initial discharges and recession constants of reservoirs 1 and 2 respectively. Coefficients for the various conditions obtained

Table 8.1: *Regression constants and coefficients of determination (CD) for the prediction of wet and dry season recession curves for the Oleolega catchment in the forested state.*

Recession Curve	Q1	Q2	K1	K2	CD
Wet Season 1990	0.044	0.114	0.967	0.543	1.00
Dry Season 1990	0.025	0.125	0.980	0.238	0.96

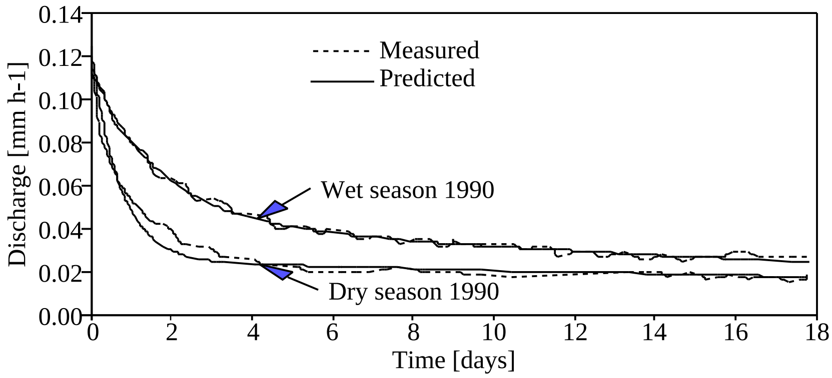


Figure 8.1: *Observed and predicted wet and dry season depletion curves for the forested Oleolega catchment.*

by Schellekens (1992) and Assenberg (1993) were recalculated using the improved stage–discharge relationship derived by Van Well (1993b), using non-linear regression techniques (Marquardt, 1963). The regression constants for both seasons are given in Table 8.1, whereas the observed and predicted recession curves are shown in Figure 8.1.

According to the theory of linear reservoirs ΔG can be calculated from the difference of the discharge at the beginning and at the end of the period under consideration using the following equation:

$$\Delta G = \frac{\partial Q}{\partial t} = \frac{Q_t - Q_0}{\ln K_1} + \frac{Q_t - Q_0}{\ln K_2} \tag{8.5}$$

Equation 8.3 was solved for the period January 4 – November 13, 1990. There were two reasons for chosing this period. Firstly, the discharge at the beginning of this period was 0.007 mm h^{-1}, whereas that at the end of the period was 0.009 mm h^{-1}, leading to the negligibly small value for ΔG of -0.1 mm. Secondly, the catchment was struck by cyclone Sina by the end of November 1990, and this of course altered the situation dramatically. An indication of the importance of ΔS for the selected period was obtained from a comparison of the rainfall totals in the four weeks preceding the beginning and the end of the period. As these compared well (11.5 mm in 1989 *versus* 22.2 mm in 1990 at Nabou station) ΔS could be neglected safely.

The total mean areal precipitation for the selected 314-day period amounted to 1547 mm, whereas total runoff amounted to 246 mm. This implied an ET of 1301

Table 8.2: *Quantification of the components of the water balance for the Oleolega catchment in the forested state between January 4 and November 13, 1990.*

Period	**P** [mm]	**Q** [mm]	**ET** [mm]	**Ei** [mm]	**Eil** [mm]	**Et** [mm]	**DeltaS** [mm]	**DeltaG** [mm]	**ET** [mm day-1]	**Eo** [mm day-1]	**ET/Eo**
Whole period Jan 4 - Nov 13, 1990	1547	246	1301	290	134	877	(0)	(-0.1)	4.14	4.40	0.94
Wet season Jan 4 - May 31, 1990	904	163	741	165	68	508	(0)	(-0.2)	5.04	4.74	1.06
Dry season May 24 - Oct 23, 1990	569	98	471	111	59	301	(0)	(0)	3.10	3.86	0.80

mm or 4.1 mm day^{-1}. The average daily ET_{pm} for the corresponding period at Tulasewa forest was only slightly higher at 4.7($\pm$1.5) mm day^{-1} (n= 300) or 1484 mm (Section 7.7). The ET value obtained for the Oleolega catchment with the catchment water balance method therefore seems realistic in view of the lower stocking and growth rate of the mature forest (*cf.* Sections 3.2 and 3.5). In addition, the assumption of zero leakage was not overturned. The Penman open water evaporation as calculated for the nearby Tulasewa site for the selected period was 4.4($\pm$1.5) mm day^{-1}, resulting in a pre-cyclone ET/E_0 ratio of 0.94 for mature pine forest at Oleolega. Blackie (1979) reported a lower value (0.77) for mature *Pinus patula* plantations growing in deep clayey soils at an elevation of 2400 m a.s.l. in Kenya. The runoff coefficient of the Oleolega catchment, defined as the proportion of rainfall that leaves the catchment as streamflow, was low at 0.16.

The ET may be further subdivided into an interception loss component and a transpiration component. An estimate of the former was obtained from the canopy and litter layer interception models discussed in Section 6.4.1 using the daily mean areal precipitation at Oleolega catchment forest as input. The (adjusted) model parameters for Koromani forest (Table 6.6) were used in the calculations since its structure resembled that of the forest in the Oleolega catchment. However, the presence of broad-leaved native vegetation (with different interception characteristics) in the riparian zone could not be accounted for. This may have resulted in small errors in the simulated interception losses. The model predicted an interception loss of 424 mm for the selected period, of which 290 mm was lost from the canopy and 134 mm from the litter layer. This would imply that 877 mm was lost through transpiration by the pines and native vegetation, and that the amount of water reaching the soil surface was 1123 mm. The values obtained for the various components of the water balance are summarized in Table 8.2

Estimates for wet and dry season water use by the forest were also obtained from selected periods during 1990. The accuracy of these estimates must be considered to be somewhat lower than those for the entire period as errors associated with ΔS and ΔG will have a larger impact on the results. An estimate for wet season ET was obtained for the 147-day period between January 4 and May 31, 1990. Groundwater storage, as calculated from Equation 8.5, was again small at -0.2 mm, whereas ΔS was neglected as rainfall totals for the months preceeding the start and the end of the period differed by only 35 mm (67 mm *versus* 32 mm).The error associated with neglecting

ΔS was estimated at less than 5%, and fell therefore within the errors of rainfall and streamflow measurements. The rainfall input during this period amounted to 904 mm, whereas the corresponding streamflow output was 163 mm. As such 741 mm were lost through evapotranspiration, or 5.0 mm day^{-1}. The corresponding daily average for Tulasewa forest (ET$_{pm}$) amounted to 5.0($\pm$1.6) mm day^{-1} as well, suggesting that the ET rates for young and mature forest during the wet season were similar, and well above the Penman open water evaporation which amounted to 4.7($\pm$1.4) mm day^{-1} (*i.e.* ET/E$_0$= 1.06). As the soil was wet for most of this period, the observed ET may be assumed to have equalled the potential ET. A summary of the components of the water balance for this period, including interception losses, is given in Table 8.2.

In a similar way, a dry season estimate of ET was obtained for a 152-day period between May 24 and October 23, 1990, when discharges were again similar implying that ΔG could be neglected. ΔS was neglected as well because the difference in rainfall within the 30-day periods before the start (45 mm) and end (72 mm) of the selected period was small. With a rainfall total of 569 mm and a total discharge of 98 mm, the estimated dry season ET amounted to 471 mm, or 3.1 mm day^{-1}. This was much lower than the corresponding ET$_{pm}$ for Tulasewa forest (4.3$\pm$1.4 mm day^{-1}), possibly due to the higher rainfall inputs in the latter area, and differences in soils (*e.g.* amounts of plant available water, Section 4.3.4), forest age and stocking. The daily average E$_0$, as measured at Tulasewa forest, amounted to 3.9($\pm$1.3) mm day^{-1} for the corresponding period, suggesting a dry season ET/E$_0$ ratio of 0.80 for the mature forest. This suggested that ET at Oleolega indeed dropped below the potential rate during the dry season, most likely as a result of the higher soil moisture deficits during periods with little rainfall (July, October).

8.4 Contribution of Baseflow and Quickflow to Streamflow

Total streamflow during a storm can be separated into a quickflow and a delayed, or baseflow component (Ward, 1984). The quickflow consists of water reaching the stream channel within a short period following rainfall, and is associated with a peak in the discharge. It may consist of contributions from various types of overland flow, lateral subsurface stormflow and channel precipitation (Dunne, 1978). Baseflow is sustained by water travelling more slowly through the system, and is for a large part derived from the depletion of soil moisture and groundwater storage within the catchment (Ward, 1984).

Schellekens (1992) tested various hydrological (Hewlett and Hibbert, 1967; Pearce *et al.*, 1976; Rogers, 1980) and hydrochemical (Nakamura, 1971) techniques, to separate the quickflow and baseflow components at Oleolega. He decided on a time-based separation method (Hewlett and Hibbert, 1967), with a straight line having a slope of 0.03 mm h^{-1} day^{-1}.

A computer programme was used (Schellekens, 1991) to analyze the streamflow for the period January 4 to November 13, 1990. The results indicated that 88 mm or 35% of the total streamflow occurred as quickflow, whereas 161 mm was assigned to baseflow. Some 85% of the total quickflow was observed during the wet season (January–April and November, 1990) whereas 58% of the quickflow occurred within five days during and after the passage of cyclone Rae in March, 1990. Baseflow during the dry season (May–October) constituted 40% of the total baseflow during the entire

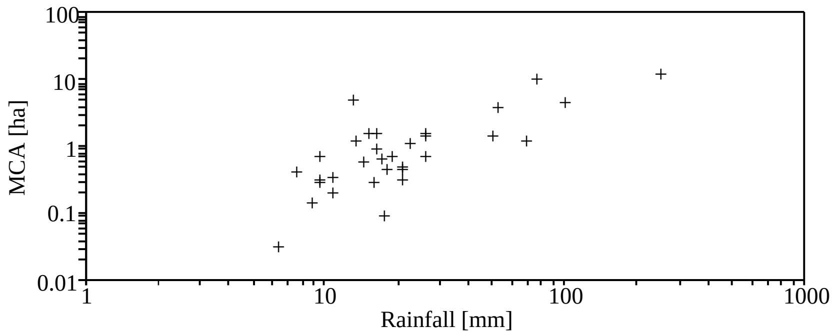


Figure 8.2: *The size of minimum contributing areas (MCA) against mean areal rainfall in the Oleolega catchment for the period January 4 – November 13, 1990.*

period.

The high quickflow percentage, particularly during cyclone events, renders the Oleolega catchment highly responsive to rainfall. Other small forested catchments in the wetter parts of the Austral–Pacific region have been reported to be even more responsive, either as a result of extremely permeable soils (as at Maimai, New Zealand; Pearce *et al.*, 1986; Sklash *et al.*, 1986), or a combination of high rainfall intensities and an impeding layer at shallow depth (as at Babinda, Queensland; Bonell and Gilmour, 1978; Bonell *et al.*, 1981).

The quickflow at Oleolega was analyzed in terms of the minimum contributing area (MCA) concept (Dickinson and Whiteley, 1970; Bruijnzeel, 1983a) by Schellekens (1992). In a general formula the MCA can be defined as:

$$MCA = \frac{Q_q}{P} \cdot A_c \tag{8.6}$$

where Q_q, P and A_c represent the quickflow volume (mm), the amount of rainfall (mm) and the catchment area (ha), respectively.

A graph of the MCAs obtained for the pre-cyclone priod in 1990 against rainfall ($P > 5$ mm) is shown in Figure 8.2. The results indicated that quickflow depended on antecedent wetness and was generally supplied by a relatively small fraction of the catchment area (63 ha) for storms smaller than 50 mm ($MCA < 2$ ha for 82% of the storms) but that the MCA could reach values up to 13 ha during larger storms (*e.g.* during cyclone Rae). The quickflow presumably consisted mainly of subsurface storm flow and valley bottom saturated overland flow with further minor contributions of channel precipitation and hillside hollow saturation overland flow (Schellekens, 1992).

Chapter 9

Summary of Hydrological Effects of Afforestation in SW Viti Levu

Estimates of the water use of *Pennisetum polystachyon* grassland and pine forest of varying age, as well as information on the climate at the respective study sites and various micro-meteorological properties of both vegetation types, have been presented separately in the previous chapters. The impact of the conversion of grassland to pine plantation forest on these various aspects will be summarized in this chapter.

9.1 Impact of Afforestation on Micro-meteorological Parameters

A summary of climatic and micro-meteorological parameters measured above grassland and two pine forests is given in Table 9.1. An attempt at evaluating the impact of afforestation on the microclimate above grassland and pine forest was made by comparing net radiation, average minimum and maximum temperatures, and average minimum and maximum relative humidities as measured above Nabou grassland, with

Table 9.1: *Dry season climatic and micro-meteorological (daytime means) parameters for grassland and pine forest. Standard deviations between parentheses.*

Location	Year	Tmin [C]	Tmax [C]	RHmin [%]	RHmax [%]	Albedo	Rn+	ra [s m-1]	rs [s m-1]
Nabou Grassland	1991	17.9 (3.0)	28.2 (1.9)	59 (9)	98 (6)	0.18 (0.01)*	8.0 (3.5)	30.8 (24.0)	246 (98)
Tulasewa Forest	1990	18.8 (2.0)	26.5 (2.1)	66 (11)	96 (4)	0.10 (0.01)	11.4 (3.6)	14.1 (8.2)	43 (21)
Koromani Forest	1991	20.4 (1.5)	26.1 (1.9)	61 (11)	89 (8)	0.13 (0.01)	10.5 (3.5)	13.5 (7.6)	113 (126)

+: Daytime values (800-1800 h) in MJ m-2 day-1; *: Wet season 1991 those measured above the mature forest at Koromani in the dry season of 1991.

The albedo decreased significantly (α= 0.01) after afforestation from 0.18–0.19 for grassland (wet season) to 0.10–0.13 for pine forest . The decrease in albedo and differences in the net long-wave radiation components caused an increase in the net radiation above the forests compared to grassland, and therefore also in the available energy for evapotranspiration: daytime net radiation totals above Koromani forest were about 24% higher than above Nabou grassland. The comparison between the grassland and Tulasewa forest was more difficult to make as R_n at the latter site was measured a year earlier. However, the even lower albedo of Tulasewa forest (0.10) suggested that the large difference in R_n between the two sites could well be caused by differences in the vegetation type, rather than in the respective seasons. The soil heat flux also showed a larger range below grass (-14 to 19 W m^{-2}) than below mature pine forest (-6 to 7 W m^{-2}), although some of the difference may be attributed to different climatic conditions between the measurement periods.

The minimum temperature and relative humidity above Nabou grassland were significantly lower (α= 0.01) than those measured above Tulasewa and Koromani forests, whereas the maximum temperature and relative humidity were significantly higher (α= 0.01). Afforestation therefore resulted in an attenuation of the diurnal patterns of temperature and humidity during the dry season, in line with the decrease in variation in soil heat flux.

These results are similar to those of Bastable *et al.* (1993), who also observed a much greater diurnal variation in temperature, humidity, and soil heat flux, as well as a reduction in net radiation over a pasture clearing (albedo = 0.16), compared to nearby undisturbed tropical rainforest (albedo = 0.13) in Brazil. The differences between forest and clearing were most pronounced during dry periods. Similarly, contrasts have been reported by Schulz (1960) for rainforest canopies and grassy clearings in Surinam, whereas various other examples of changes in microclimate after forest clearing can be found in Lal (1987).

The aerodynamic properties of the grassland were also different from those of pine forest, which presents a much rougher surface. This must have resulted in a gradual decrease in r_a during the first few years after the planting of the pine forest. However, the decrease seemed to level off after canopy closure as differences in r_a between the young and the mature stand were not significant (*cf.* Section 7.6.3). As will be shown below, the combined effect of increases in LAI and reductions in r_a associated with afforestation resulted in a large increase in amounts of rainfall interception by the respective vegetation types (Table 9.2; *cf.* Calder, 1979; Calder, 1982).

The *Pennisetum polystachyon* grassland vegetation was strongly seasonal and started to die off at the start of the dry season. Stomatal resistances were high during the dry season and this, in combination with a gradual decrease in LAI, resulted in a corresponding increase in daytime r_s from about 80 s m^{-1} in May to 300–400 s m^{-1} at the end of the dry season. Differences in r_s of grassland and pine forest were small at the beginning of the dry season (Calder, 1979), but increased as the dry season progressed because the r_s of the pines, which did not show a seasonal trend, remained fairly constant (*cf.* Sections 5.4.4 and 7.6.3).

Table 9.2: *Dry season (May 11 – September 19, n= 132) and annual estimates of ET, E_0, modelled interception losses, and rainfall amounts (P) for Nabou grassland and Tulasewa, Korokula, Koromani and Oleolega forests .*

Location	**Period/Year**	**ET** [mm]	**ET** [mm day-1]	**Eo** [mm]	**ET/Eo**	**I-loss Canopy** [mm]	**I-loss Litter** [mm]	**I-loss Total** [% of P]	**Rainfall Total** [mm]
Dry Season Estimates									
Nabou Grassland	1991	128	0.97 (0.34)	485	0.26	14	25	12	319
Tulasewa Forest	1990	521	3.95 (1.14)	468	1.11	92	51	31	465
Koromani Forest	1991	382	2.96 (1.14)	551	0.69	49	45	30	317
Oleolega Forest*	1990	438	3.3 (-)	506	0.87	100	50	29	525
Annual Estimates									
Tulasewa Forest	Nov'89-Nov'90	1772	4.85 (1.56)	1681	1.05	357	159	27	1932
Korokula Forest	1990					365	154	29	1779
Koromani Forest	1990					335	155	26	1908
Oleolega Forest+	1990	1512	4.1 (-)	1605	0.94	338	156	27	1798

*: ET and Eo based on data collected in the period May 24 - October 23, 1990
+: Annual totals of ET, Eo, I-loss, rainfall and runoff obtained by extrapolation from 314 days of data

9.2 Impact of Afforestation Dry Season on Water Use

Grassland ET rates in the dry season were determined from a combination of the Penman-Monteith equation and soil moisture depletion measurements (Sections 5.3 and 5.4.4). Estimates for the dry season water use of Tulasewa and Koromani forests were obtained from soil moisture depletion measurements (Section 6.5), and particularly from micro-meteorological measurements (Section 7.7). A comparison of the results obtained with the two approaches indicated that the former method underestimated ET at Tulasewa and Koromani forests by 24% and 38%, respectively, due to water extraction by tree roots at depths beyond those reached by the soil moisture probe access tubes. Because the access tubes in the grassland plot extended below the rooting depth of grass, the ET_{sm} data obtained with the soil moisture depletion method were considered realistic in this case. Finally, the catchment water balance method was used to obtain a dry season estimate of water use by mature pine forest at Oleolega.

Dry season and annual estimates of ET, E_0, rainfall and interception losses for Nabou grassland (no annual values), and Tulasewa, Korokula (no estimates for ET, E_0), Koromani and Oleolega forests are summarized in Table 9.2. It should be noted that that the estimates presented here were collected over part of the respective dry seasons (only 132 days), and that totals pertaining to a whole dry season (184 days) will therefore be considerably higher. The post-cyclone dry season water use of Koromani forest was 254 mm higher than that of Nabou grassland in 1991. This was largely due to differences in transpiration (calculated as the difference between ET and interception loss) between the two vegetation types (79 mm for grass *versus* 288 mm for mature pine forest) and to a lesser extent to differences in interception loss (39 *versus* 94 mm, respectively). The dry season ET for grassland would probably have been higher in 1990, due to the higher 1990 rainfall total which would have resulted in a larger interception loss. It should be mentioned here (*cf.* Section 5.1) that the *Pennisetum polystachyon* grasslands in SW Viti Levu were observed to die anyway during the dry season, regardless of soil water conditions. Therefore no major increases in transpiration as a result of increased rainfall were to be expected for 1990. Further support for the latter contention comes from the fact that E_0 values differed by less than 5% for the two dry seasons. The total interception loss for the grassland during the dry season of 1990 was approximated at 12% of total rainfall (Section 5.5) or 60 mm. Together with the estimated transpiration rate of 80 mm (1991 value) a total dry season ET of 140 mm was calculated. Using this value, corresponding ET losses at Tulasewa and Oleolega were 380 and 300 mm higher than that of the Nabou grassland, respectively.

The annual ET in the fast-growing and well-stocked Tulasewa forest was high, amounting to 92% of the annual rainfall, and somewhat lower in the cyclone damaged mature Oleolega forest where it amounted to 82% of the annual rainfall (Table 9.2). The interception losses, again expressed as fractions of total rainfall, did not show much variation between forest sites and were in the order of 500 mm year^{-1} for a year of average rainfall. Annual transpiration totals ranged from about 1050 mm at Oleolega to 1256 mm at Tulasewa, which is within the range for natural forest in humid tropical lowlands (885–1285 mm year^{-1}) given by Bruijnzeel (1990).

Summarizing, conversion of *Pennisetum polystachyon* grassland to *Pinus caribaea* forest resulted in increases in dry season transpiration rates and in amounts of water lost by rainfall interception (Table 9.2). Annual differences in ET between grassland and pine forest will be larger than the quoted 250–380 mm, as measurements pertained to (part of) the dry season only. The water use of *Pennisetum polystachyon* grass during the wet season remains unknown as yet, but is almost certainly lower than that of the pine forest due to its lower rainfall interception (estimated at 12% *versus* 26–29% of rainfall in mature pine; *cf.* Sections 5.5 and 6.4.1), and the lower net radiation total observed above the grass.

The annual streamflow total of the forested Oleolega catchment was 288 mm in 1990 (Section 8.3), and since the difference in the dry season ET between the vegetation types was 250–380 mm, the annual streamflow total from a similar catchment under grass was likely to exceed 540 mm. This suggests that a reduction in annual water yield of at least 50% may be expected several years after grassland catchments have been converted to pine plantation forest (*cf.* Kammer and Raj, 1979). However, further work on wet season stomatal behaviour and LAI, preferably in combination with a micro-meteorological study involving the determination of ET_{pm} from a combination of the temperature fluctuation energy balance method (to obtain expressions for r_s; see Section 7.6.3) and the Penman-Monteith model, of *Pennisetum polystachyon* grassland is necessary before grassland ET in the wet season can be quantified properly.

9.3 Effect of Cyclone Sina on Forest Water Use

Temporary reductions in transpiration as well as in interception losses may be expected after the passage of a cyclone due to the decrease in foliar biomass (LAI) (*cf.* Frangi and Lugo, 1991; Lodge *et al.*, 1991).

Comparison of pre- and post-cyclone dry season ET_{sm} (Table 6.8) indicated that water extraction from the top 0.6–1.0 m of the soil decreased by 31%, 38% and 8% in Tulasewa, Korokula and Koromani forests, respectively, 6–9 months after the forests had been damaged severely by cyclone Sina in November, 1990. In the Tulasewa forest plot where tree density was reduced by some 40% this resulted in much higher soil moisture levels throughout the dry season of 1991 compared to 1990 (Figure 6.5 in Section 6.5).

Cyclone damage was less in Korokula and Koromani forests, however, and no such differences in minimum soil moisture levels between the pre- and post-cyclone dry seasons were observed there. The relatively large reduction in ET observed for the Korokula forest plot in 1991 could partly be attributed to differences in rainfall amounts between the respective periods. However, the fact that moisture stress was observed during the rather wet dry season of 1990 (as indicated by increased litter fall; Section 12.3.1), but not during that of 1991, which was much drier, suggested that a reduction in ET as a result of cyclone damage had occurred at this site as well.

Comparison of the pre-cyclone dry season ET of Oleolega forest with the post-cyclone ET in Koromani forest (which was similar in structure) suggested a 10% reduction in ET as a result of damage afflicted by cyclone Sina. The actual reduction may have been somewhat higher as E_0 in 1990 was lower than that for the corresponding period in 1991 (table 9.2).

Interception losses from the canopy decreased at all sites (Section 6.4), as indicated by the larger amounts of relative throughfall collected during the post-cyclone period. The largest decrease was observed at Korokula forest, where the observed amount of throughfall increased from 77% of total rainfall during the pre-cyclone period to 87% during the post-cyclone period. At Tulasewa forest relative throughfall increased from 79% to 85% of total rainfall. No pre-cyclone measurements had been made during the 1990 wet season in the Koromani forest plot, and the observed 82% of total dry season rainfall in 1990 *versus* 83% of post-cyclone rainfall may not accurately reflect the effect of cyclone Sina. However, the decrease in interception loss from the canopy was partly compensated by higher interception in the litter layer, which increased from 9.9% to 11.6% of total rainfall in Korokula forest, and from 9.5% to 10.5% in Tulasewa forest. We are not aware of any other studies in the literature reporting the effects of forest disturbance by tropical cyclones on rainfall interception or forest evapotranspiration.

Part III

Nutrient Dynamics

Chapter 10

Grassland Biomass and Nutrient Content

10.1 Introduction

In the following sections a description of the above-ground biomass of the Nabou grassland site and its associated nutrient content will be given to illustrate the grassland, *i.e.* the pre-planting, situation. In subsequent chapters forest biomass and nutrient content, as well as rates of nutrients inputs, intra-system cycling, and outputs will be discussed.

10.2 Field and Laboratory Procedures

Estimates of the dead and live standing crop at the Nabou grassland site were made at the end of February (growing season) by clearing an area of $2{*}1$ m^2, and in May 1991 (start of the dry season) by clearing another $3{*}1$ m^2. All vegetation was cut at ground level after which litter layer and green plants (including any dead material still attached to the plants) were separated and put in pre-weighed plastic bags for transport. No attempt was made to sample the below ground-biomass. Field weights were recorded within a few hours after sampling with a Sartorius electronic weighing scales capable of weighing 6100 g with an accuracy of 0.1 g. All dry weights referred to in this chapter were obtained after drying of the samples in an oven, made available by TROPIK Wood Industries Ltd. at 70°C for at least 3 days.

The specific leaf area (SLA) of *Pennisetum polystachyon* grass was determined by measuring the surface area of 50 randomly picked, fresh leaves and recording their total dry weight. The surface area was determined shortly after sampling by carefully drawing the contours of each leaf on paper and measuring the total area by planimeter.

To determine the biomass of dead and green leaves, seed plumes and stems, 50 plants were randomly selected and cut at ground level in May 1991. Amounts of each component were bulked for 10 plants, placed in pre-weighed plastic bags, dried and weighed. In this way five replicas were obtained for each plant component described before.

Another 66 plants were sampled in a similar way between July 23 and August 10. To obtain additional information on biomass distribution with height of the plant, the length of each plant was measured, after which it was cut into three sections (0–0.7 m, 0.7–1.4 m and 1.4 m–top). The weights of dead leaves, fresh leaves and stems in each section were recorded. Seed plumes were not present as the flowering period had finished two months earlier.

A sunfleck ceptometer (Decagon Devices Inc., model SF-80) was used to determine canopy gap fraction and the absorbance of photosynthetic active radiation (PAR) at three levels within the vegetation during two days with clear-sky conditions. The canopy gap fraction was measured as the fraction of the light sensors receiving radiation above a certain treshold value, which represented the PAR value measured in the shadow of grass. After some experimenting the treshold value was set at 250 μmol m^{-2} s^{-1} (about 25% of incoming PAR). Measurements were made by inserting the probe horizontally above the litter layer (0.15–0.3 m) and at 1.0 m and 1.4 m within the vegetation (maximum height $\pm$1.8 m). Incoming PAR was measured every few minutes in an adjacent area with low vegetation. A total of 217 measurements were made just above the litter layer on July 9 between 9:27 and 10:13 h with the sun angle increasing from 33° to 40°. Measurements at higher levels in the canopy were postponed to the next day to avoid effects of variations in sun angle on PAR and canopy gap fraction measurements. One hundred and ten measurements were made at the 1 m level on July 10, between 9:15 and 9:51 h, and another 106 measurements at 1.4 m between 9:51 and 10:09 h.

Two subsamples were taken from bulk samples of grass litter and fresh grass collected in February for analyses of macronutrients (N, P, K, Ca, Mg) and micronutrients (B, Mn, Zn). The oven-dry subsamples were sent to the Forest Research Institute, Rotorua, New Zealand, packed in paper enveloppes for analysis.

Macronutrients were digested with an H_2SO_4/H_2SO_4 solution on a digestion block (Parkinson and Allen, 1975). Nitrogen and P were simultaneously determined by automated colorimetric methods (indophenol blue method and vanadomolybdophosphoric yellow method respectively) whereas K, Ca and Mg were determined by atomic absorption. Manganese and Zn concentrations were established by atomic absorption after the material was ashed for four hours in a muffle furnace at 500 °C and the ash dissolved in hydrochloric acid. Boron was determined on the same digest using a curcumin colorimetric method. A more detailed description of the methods used by FRI is given in Nicholson (1984).

10.3 Grassland Biomass and Structure

Pennisetum polystachyon grass accounted for 92 and 93% of the total grassland biomass in February and May, 1991, respectively. The above-ground living biomass of *Pennisetum polystachyon* grass was 6486($\pm$1747) kg ha^{-1} at the end of February and increased to 8239($\pm$1427) kg ha^{-1} in May, which may be close to the maximum attained value as the vegetation started to die off soon after. The remainder was made up by ferns (*Dicranopteris linearis*), sensitivity grass (*Mimosa pudica*) and blue rats tail (latin name unknown) with a combined average biomass of 553($\pm$689) kg ha^{-1} in February and 609($\pm$190) kg ha^{-1} kg ha^{-1} in May, 1991. The productivity of Nabou grassland was 1809 kg ha^{-1} during the 76-day period. Production rates of mission grass and Nadi blue grass (which appeared recently in the grasslands near Nadi but has not yet spread to the Nabou area) are given in Table 10.1. These production rates were measured on

Table 10.1: *Production rates (dry weights in kg ha^{-1}) of mission grass (Pennisetum polystachyon) and Nadi blue grass (Dichanthium caricosum) as measured at Nacocolevu Research Station near Sigatoka by the Pastures Research Unit from the Ministry of Primary Industries of Fiji. (Mr. S. Chand, pers. comm.).*

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	Total
Mission grass	523	850	1100	1085	1090	220	190	190	198	225	500	475	6646
Nadi blue grass	475	775	1000	840	600	200	175	176	180	200	450	425	5496

trial plots (9 m^2) each at the nearby Sigatoka Research Center at Nacocolevu. The productivity was highest during the wet season (December–May) with a yield of 5123 kg ha^{-1} as compared to 1523 kg ha^{-1} during the dry season. The productivity of the Nabou grassland in March and April 1991 (1750 kg ha^{-1}) was somewhat lower than the corresponding value (2180 kg ha^{-1}) given in Table 10.1. The productivity of the grass vegetation was highly variable anyway in SW Viti Levu, depending on the site quality, and the figures presented here for Nabou grassland may be assumed representative (Mr. T.T. Rawaqa, pers. comm.).

The average gravimetric moisture content of the grass at the Nabou site decreased from 251% of dry weight in February to 158% in May, possibly reflecting increased moisture stress (*cf.* Section 5.3). The decrease in moisture content was less pronounced for the other species (159% *viz.* 133%).

The mass of litter standing crop was 10581(±146) kg ha^{-1} in February and had decreased to 6869(±1035) kg ha^{-1} in May 1991. Most of the grass died between May and July and the May estimate of litter mass may therefore be considered to be close to the annual minimum. A maximum litter mass of about 15000 kg ha^{-1} can be expected at the end of the dry season (November) when most of the grass has died. The seasonal variation of the combined mass of living grass and litter should not be very high and fluctuated presumably between an estimated 15000 kg ha^{-1} at the end of the dry season to 17000 kg ha^{-1} in February.

The mean vegetation height was estimated visually at 1.5 m in February (maximum 2.5 m), 1.8 m in May, 1.4 m by the end of July and 1.2 m in September 1991. However, the length of 66 individual plants sampled between July 23 and August 10 ranged from 0.79 m to 2.39 m with an average of 1.81(±0.36) m and the visually determined decrease in average height during the dry season must therefore be due to wind lean of the dead grass. The average dry weight of a single plant (including dead leaves) was 7.0(±0.3) g in May (n= 50) and 7.5(±1.1) g by the end of July (n= 66). Stem weight accounted for about 68% of plant weight in May as well as in July. Dead leaves, green leaves and seed plume weights accounted for 10%, 14% and 9% of total plant weight, respectively, in May. The weight of dead leaves increased to 25% by the end of July, coinciding with a decrease in the weight of green leaves to 7% and a total absence of seed plumes. The biomass of each plant component for each height interval was calculated by multiplying the biomass values with the mass fraction of each component for each height interval. Figure 10.1 shows the cumulative distribution of dead leaf, green leaf and stem biomass *versus* height of the vegetation by the end of July. It is clear that by this time fresh leaves were concentrated in the 0.7–1.4 m level and made up only a minor part of the total biomass. At the beginning of September

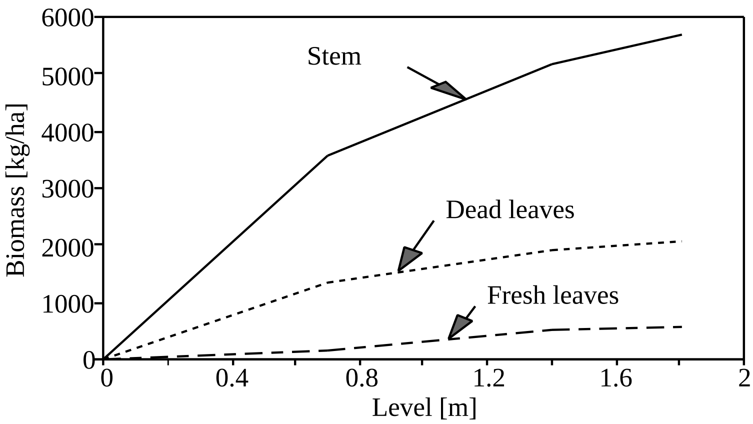


Figure 10.1: *Cumulative biomass of dead leaves, fresh leaves and stem* versus *height of the Nabou grassland vegetation at the end of July 1991.*

Table 10.2: *Estimates of living and dead biomass for the Nabou grassland site at different times of the year and derived estimates of LAI.*

Date 1991	**Total biomass** kg m-2	**Dead leaves** kg m-2	**Fresh leaves** kg m-2	**Stem** kg m-2	**Seed** kg m-2	**SLA** kg m-2	**LAI** m2 m-2
February 23-28	0.687	-	(0.178)a	(0.508)a	-	(11.4)b	2.0
May 11	0.824	0.081	0.112	0.560	0.071	11.4	1.3
July 23 - August 10	(0.824)c	0.207	0.055	0.561	-	(11.4)b	0.6
September 1	(0.824)c	(0.247)d	0.016	0.561	-	(11.4)b	0.2

a: Dead leaves were assumed absent, grass not yet in flowering stage therefore no seed.
b: Using the SLA as determined on May 11.
c: Total grass biomass assumed to remain constant after May 11.
d: All foliage above 0.7 m dead (visual observation). Fraction of living leaf mass below 0.7 m to total plant mass, as determined between July 23 and August 10, used in the calculation of LAI

all leaves above a height of 0.7 m had died (visual observation) but some green plants were observed below this level. The distribution of biomass between dead leaves, green leaves and stems as well as approximate LAI values at different times of the year are shown in Table 10.2.

Estimates of LAI were obtained by combining the estimated green leaf biomass with the SLA. The SLA of mission grass was estimated at 11.4 m^2 kg^{-1} in May and multiplying this value with the fresh leaf biomass of 1121 kg ha^{-1} yielded an LAI of 1.3 m^2 m^{-2}. An approximation of the LAI for February was made by assuming that all leaves on a plant were green at that time (no moisture stress in the wet season) and that both the leaf to leaf+stem mass ratio and the SLA were similar to those in May. As it unlikely that the SLA will vary much throughout the year, the main error will be associated with the calculated green leaf mass fraction which was estimated at 25% of the total plant mass in February (Table 10.2). No actual leaf biomass and SLA data were available to calculate the LAIs for July, August or September. However, total

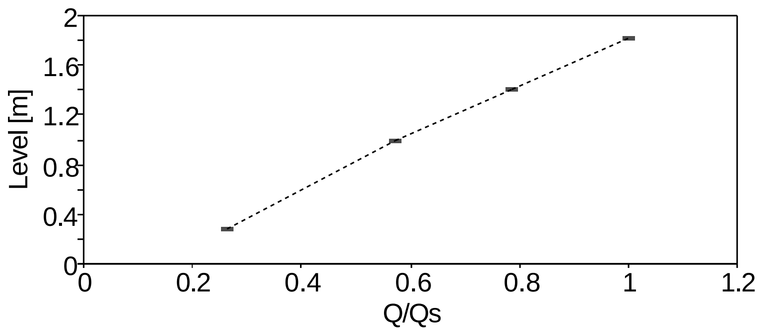


Figure 10.2: *PAR fractions (Q/Q_s) received at several levels within the grass cover.*

biomass for May may be taken as a good approximation as both decomposition and production of biomass are low during the dry season. The distribution of the biomass over the various plant components was determined at the end of July (Section 10.2) and the fresh leaf biomass was obtained by combining the May biomass value with the fraction of fresh leaf mass to total plant mass. Using the SLA value for May the LAI at the end of July was estimated at 0.6 m^2 m^{-2}. On the first of September all leaves above a height of 0.7 m had died and the fresh leaf mass fraction of the 0–0.7 m level (2% of total plant mass), determined between July 23 and August 10, was used to calculate an LAI of 0.2 m^2 m^{-2} from the May biomass and SLA values, which may be considered as the seasonal minimum. This shows that the seasonal variation in grassland LAI is large with a 10-fold difference between the wet season maximum and the dry season minimum. The estimated wet season value of 2.0 m^2 m^{-2} is much higher than the 0.8($\pm$0.3) m^2 m^{-2} found for short grass with a much lower biomass (biomass of grass and litter amounted to 5600 kg ha^{-1}) by McWilliam *et al.* (1993) in a clearing in Amazonia.

The PAR fraction (Q/Q_s) varied from 0.27($\pm$0.15) just above the litter layer to 0.79($\pm$0.11) at 1.4 m as shown in Figure 10.2, with incoming PAR (Q_s) ranging from 860 to 1090 μmol m^{-2} s^{-1}. The canopy gap fraction increased from 35$\pm$24% just above the litter layer to 79$\pm$16% at 1.0 m and 97$\pm$5% at 1.4 m. As shown in more detail in Section 11.2, if the LAI is known the light extinction coefficient (κ) of a canopy can be calculated from the PAR fraction using the Beer-Lambert equation (Pierce and Running, 1988). The extinction coefficient κ is an empirical parameter depending on the geometry of the canopy and ranges from 0.3 to 1.5, with the lower values corresponding with an erectophyl type of canopy (Ross, 1975). Ripley and Redman (1976) found an extinction coefficient of 0.63 for short grass in the temperate zone. Linear interpolation of the derived LAI estimate for May and July-August 1991 resulted in an LAI of 0.8 m^2 m^{-2} on July 10 (*i.e.* the day that the PAR profile of Figure 10.2 was determined). For a measured PAR fraction of 0.27 just above the litter layer, κ would have the very high value of 1.64, which must be attributed to the large amount of PAR intercepted by the grass stems and various kinds of dead material.

Table 10.3: *Concentrations of nutrients in Pennisetum polystachyon grass and litter at the Nabou study site. Macronutrients in %, micronutrients in ppm.*

	N	P	K	Ca	Mg	B	Mn	Zn
Litter	0.497	0.030	0.070	0.359	0.129	20	337	5.5
Mission grass	0.469	0.043	1.328	0.223	0.241	15	284	3.9

Table 10.4: *Total amounts of nutrients (kg ha^{-1}) stored in Pennisetum polystachyon grass and grassland litter at the Nabou study site.*

	N	P	K	Ca	Mg	B	Mn	Zn
February 1991								
Litter standing crop	52.5	3.2	7.4	37.9	13.6	0.058	3.566	0.206
Mission grass	30.4	2.8	86.1	14.4	15.6	0.025	1.842	0.097
Total	*82.9*	*5.9*	*93.5*	*52.4*	*29.2*	*0.083*	*5.408*	*0.304*
May 1991								
Litter standing crop	34.1	2.1	4.8	24.6	8.9	0.037	2.315	0.134
Mission grass	38.6	3.5	109.4	18.3	19.8	0.032	2.340	0.124
Total	*72.7*	*5.6*	*114.2*	*43.0*	*28.7*	*0.070*	*4.655*	*0.258*

10.4 Grassland Nutrient Content

The concentrations of macro- and micronutrients in litter and fresh grass sampled in February 1991 are shown in Table 10.3. The concentrations of N, Ca and the micronutrients were higher in the litter, indicating that these nutrients may be released relatively slowly during decomposition. The concentration of K, on the other hand, was 18-fold higher in living grass than in litter, suggesting that K is easily leached. Concentrations of Mg and P were also higher in living grass but the difference was much less pronounced than for K. Nye and Greenland (1960) provided ranges of 0.29–1.8 for N, 0.05–0.14 for P, 0.54–1.2 for K, 0.17–0.42 for Ca and 0.29–0.35 for Mg. With the exception of K, the concentrations in the Nabou grass were at the lower ends of these ranges.

The amounts of nutrients stored in the grassland vegetation and litter were calculated for February and May, assuming that the concentrations did not change in time (Table 10.4). Amounts of nutrients stored in the litter layer generally exceeded those stored in the living crop in February, with the exception of K, and to a lesser extent Mg, which had a very low concentration in the litter. By the end of the growing season, however, substantial amounts of nutrients (presumably released from the litter layer through decomposition) had been taken up by the vegetation and amounts stored in the living plants exceeded those in the litter layer with the exception, mainly, of Ca. Interestingly, total amounts of nutrients stored in the living crop and litter layer decreased slightly (with the exception of K) as the dry season progressed, despite an overall increase in biomass from 7040 to 8848 kg ha^{-1}. This is thought to reflect the decrease in mass of the litter layer which was larger than the increase in living biomass (*cf.* Table 10.2).

Because the estimated seasonal variation in the combined mass of living grass and litter was not very large and the concentrations of N, P, Ca, B, Mn and Zn in fresh grass were not dramatically different from those in litter the total amounts of these nutrients stored in the vegetation should not show a very large seasonal variation either. However, K, and to a lesser extent Mg, may well show a large seasonal variation with progressively higher concentrations during the growing season, a rapid decline at the end of the growing season coinciding with the dying of the grass, and low levels during the dry season. Further work is necessary to test these assertions.

A rate of litter turnover (K_L) can be calculated as the ratio of the annual litter production to the litter standing crop (Swift *et al.*, 1979; Gunadi, 1993b; Burghouts, 1993). Such an estimate was obtained for the Nabou grassland site using the annual production rate of grass and the seasonal minimum litter standing crop (*cf.* Section 12.4). The grass vegetation is highly seasonal and dies off almost completely during the dry season. The annual production of grass litter can therefore be approximated by the annual grass production, which was estimated at 6646 kg ha^{-1} (Table 10.1). With a seasonal minimum litter standing crop of 6869 kg ha^{-1} as observed in May 1991, a K_L value of 0.97 was obtained. The rate of decomposition was highest during the wet season as indicated by the loss of 3712 kg ha^{-1} of litter between February 28 and May 10. As such most nutrients released from the decomposing grass litter can be used by the growing crop.

Chapter 11

Forest Biomass and Nutrient Content

11.1 Introduction

In this chapter a description will be given of the accumulation of biomass and nutrient content in *Pinus caribaea* plantations over a period of a rotation. Basic information on the structure of the forest at the respective experimental sites has already been presented in Sections 3.2 – 3.4. More detailed information including diameter and height distributions, pre- and post-cyclone growth rates and LAIs will be presented in this chapter to obtain insight into the changes in forest structure during a rotation period, which often involves damage by cyclones.

11.2 Methods and Field Procedures

Tree diameter and height surveys were carried out in the Tulasewa (n= 157), Korokula (n= 100) and Koromani forest plots (n= 100) between January and March 1990 and between July and September 1991. Measurements were also made on 10–15 trees in each plot in June and July 1990 and in January 1991 to obtain growth rates for 1990. An additional 106 trees were measured in the Tulasewa forest plot in July 1990 and 368 trees in Koromani forest in July and August 1991 to obtain information on the forest structure surrounding the meteorological towers (*cf.* Chapter 7). Diameters at breast height (1.35 m) over bark (*Dbhob*) were measured with a diameter tape with a resolution of 0.1 cm. Tree height (h) and the height of the lowest branch with green needles (crown depth) were measured with a Haglöf clinometer and a measuring tape. Estimates of the mean tree height, obtained with the clinometer, differed by less than 2% from the actual mean height of 39 trees. However, for individual trees the error in the clinometer estimates could be up to 15%. Estimates of the crown diameter were obtained by measuring dimensions of the projected crown at ground level with a measuring tape within the planting row and perpendicular to it.

In each age class (7, 12 and 16 years in 1991) five trees, with diameters and heights close to the stand averages, were destructively sampled for above-ground biomass estimations. One tree (tree A141) was sampled before the passage of cyclone Sina in

November 1990, the other trees were sampled between March and September 1991. No attempts were made to obtain estimates of below-ground biomass as the stumps of harvested trees are left *in situ* and therefore do not represent a net loss of nutrients. All trees were cut at a height of about 0.2 m with a chainsaw after the diameter, height, crown depth and crown diameters had been measured. The fresh weights of dead and green branches (diameter $\geq$1 cm), twigs (diameter $<$1 cm), needles, cones and male flowers were determined in the field for each two meter section of the living crown. Subsamples of each component were taken at each level to obtain factors for the conversion of fresh weights to dry weights and for chemical analysis. After the tree had been stripped from its crown the stem was cut into one-metre sections and 2 cm thick disks were collected from each section up to slash point (diameter over bark of 7 cm). Separate disks for chemical analysis were collected at the base of the tree, at the point with a diameter over bark (Dob) of 10 cm and at the level where $Dob = (Dob_{base} + Dob_{10cm})/2$. Fresh weight of each disk was recorded and the Dob measured, after which bark was separated from stemwood. Fresh weights of bark and stemwood were recorded and the diameter under bark (Dub) measured. For each trunk section bark weight was calculated from the mean bark to stemwood ratios of the disks collected at the two ends of the section. A rough estimate of the fresh bark and stemwood density was obtained by carefully placing in water and recording the height of the wetted area. The volume of each disk was measured as a function of its diameter and thickness as determined at six points with a calliper (precision 0.05 mm). The total dry weight of each component per tree was calculated by multiplying the total fresh weight of that component by the ratio of dry to fresh weight as determined from subsamples.

Weighed bulk samples were taken from stemwood, bark, dead branches and twigs and green branches and twigs for chemical analysis. Foliage samples were bulked such that representative samples were obtained for the lower, middle and upper levels of the canopy and for dead foliage. As the sample size was small the *Student's t* distribution was used to test whenever average concentrations in tree components differed between sites.

Nutrient concentrations in harvestable timber (wood and bark) for the Oleolega catchment were determined from disks collected from 12 trees according to the method described above. Five representative locations were selected within the catchment and 2–3 trees were sampled at each location in December 1990. The locations, coded A–E, are shown on the map given in Figure 15.3.

All samples were sent to the Forest Research Institute in New Zealand for analysis of N, P, K, Ca, Mg and B, Mn and Zn (foliage only) as described in Section 10.2.

An attempt was made to obtain relationships between available nutrients in the topsoil around the sample trees and corresponding concentrations in stemwood and foliage of those trees. Two soil samples were collected within 50 cm of the stumps immediately after the trees were sampled for biomass. The samples for each depth interval (0–10 and 10–20 cm) were bulked to account for spatial variations. The samples were air dried and analysed for exchangeable Na, K, Mg, Ca, NH_4, 'available' P and soluble NO_3, as well as for pH_{H2O}, pH_{KCl} and loss on ignition as described in Chapter 4. The analytical data are presented in Appendix 26.

Allometric regression equations (Pardé, 1980; Madgwick, 1983) were used to calculate weights of tree components as well as that of whole trees as a function of the stem volume ($Dbhob^2h$). Stand biomass (kg ha^{-1}) was calculated as the sum of the weights of the individual trees or tree components divided by plot area. Nutrient contents (kg ha^{-1}) were calculated as the product of the biomass of each component times the average concentration of the respective nutrient in that component.

The specific leaf area (SLA) was determined on 146 individual needle sets collected in Tulasewa forest and on 90 needle sets collected in Koromani forest (Opdam, 1993). The surface area of each individual set was calculated from needle length (l) and average thickness, as determined at $0.25 * l$ and $0.75 * l$ (Swank and Schroeder, 1974; Kaufmann and Troendle, 1981). Needle sets consisted mostly of three individual needles although sets containing two, four or five needles were not uncommon. When all needles within a set were grouped together a cylindrical shape was formed of which the radius was equal to the thickness of the needle. The surface area of the set was calculated from the length and the radius (r) following Equation 11.1 where n represented the number of needles in a set (3, 4 or 5). The fresh weight of each group of five sets was determined as well as the dry weight of all sets combined together.

$$2\pi rl + 2nrl \tag{11.1}$$

Information on the distribution of weight and moisture content of individual needle sets with height of the crown was obtained by randomly collecting 100 fresh needle sets within each 1 m section of the live crown from 14 trees and recording their fresh and oven-dry weights.

Estimates of pre- and post-cyclone LAIs for each of the study forests were calculated from the SLA, the foliage biomass and the tree density. Independent estimates were obtained using the Decagon Sunfleck ceptometer described earlier according to the method of Pierce and Running (1988). Several transects were made through each forest and at every 3 m along a transect 20 PAR (Q) measurements were made by holding the ceptometer level with arms outstretched and sampling while turning a 360° circle at about 15° increments. Measurements of incoming PAR (Q_s) were made regularly in adjacent grasslands. The Beer-Lambert equation (Equation 11.2) was used to calculate the LAI using an extinction coefficient (κ) of 0.52 as given by Jarvis *et al.* (1976) and confirmed by Pierce and Running (1988) for coniferous forests.

$$LAI = -\frac{\ln(Q/Q_s)}{\kappa} \tag{11.2}$$

Pre-cyclone measurements were made in Tulasewa forest only (July 1990, n= 50), whereas post-cyclone measurements were made in Tulasewa (n= 60), Korokula (n= 105) and in Koromani (n= 74) forests in July 1991. Another 131 measurements were made in the forest surrounding the meteorological tower near the Koromani forest plot. All measurements were made between 11:00 and 14:00 h under clear skies. Canopy gap fractions were determined in the same fashion and using the PAR treshold described in Section 10.2

The above-ground biomass of the undergrowth was measured in Koromani forest on May 5, 1991. All undergrowth vegetation in two squares, covering an area of 25 m^2 each, was cut at ground level and the total fresh weight for each species was recorded. Factors for the conversion of fresh weight to dry weight were obtained from subsamples collected for each species.

11.3 Tree and Forest Characteristics

In this section some background information is given on tree structure, as well as wood and foliage properties of *Pinus caribaea* Morelet var. *hondurensis* grown in Fiji, as obtained from the literature and the present study. The information has been included as some of it may be of importance for forest fire prediction models (pers. comm. Dr. M.E. Alexander) or as future reference for studies on pine plantation forests in Fiji. Furthermore, tree and forest structure have a large influence on the surface roughness parameters used for the calculation of evapotranspiration with various micro-meteorological techniques (Chapter 7).

11.3.1 Tree Structure

Changes in the mass–height distributions of stems, branches, foliage and total biomass during a rotation are shown in Figures 11.1A–D, respectively. Measured weights were converted to t ha^{-1} using the pre-cyclone biomass data presented in Section 11.5.

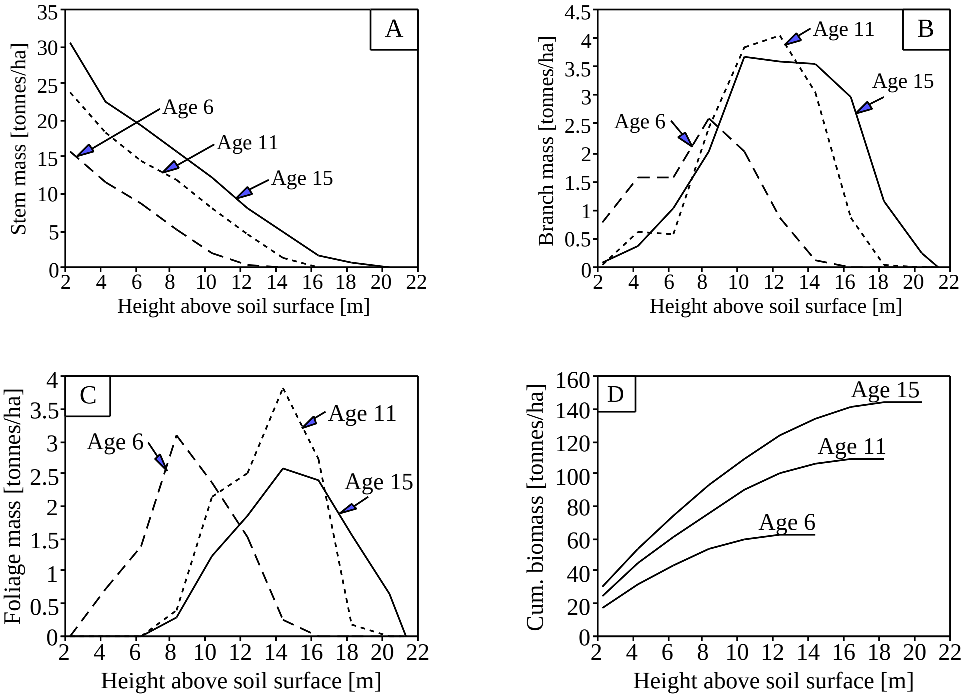


Figure 11.1: *Height distributions of stem biomass (A), branch biomass (B), needle mass (C) and cumulative total mass (D) for each of the forest plots.*

Information on the growth rates of the respective forests is presented in Section 11.3.4 and it suffices to say that annual diameter increments were much higher in the Tulasewa forest plot than in the Korokula and Koromani plots for which similar values were measured. Figure 11.1A shows that a large proportion of the stem biomass is contained in the lower part of the stem. The curves for the respective age classes are roughly parallel indicating that the stem form remains fairly constant throughout the rotation. The stem form can be described by the taper ($Dbhob/h$), which increased slightly with age from 0.0133($\pm$0.002) m m^{-1} at age six (n= 248) to 0.0139($\pm$0.003) m m^{-1} at age 11 (n= 100) and 0.0149($\pm$0.004) m m^{-1} (n= 450) at age 15. Similar values (range 0.0116–0.015 m m^{-2}) for the taper of *Pinus caribaea* were found in plantations in Nigeria (Egunjobi, 1975, 1976; Kadeba, 1991) whereas slightly higher values were observed in Puerto Rico (0.015–0.0175 m m^{-1}; Lugo, 1992).

Figures 11.1B and 11.1C show the development of the crown over a rotation period. Both branch and foliage mass were highest at the mid-crown position for all age classes. The low branch mass at age 6 as compared to those at age 11 and 15 shows that the crown was not yet fully developed at this age, although the foliage mass-height distribution curve was already similar in shape to those of the older forests (Figure 11.1C).

Branch angles were measured at the stem and at a distance of 50 cm from the stem on tree A141 in Tulasewa forest. At the base of the crown (2 m) branches pointed upwards at low angles ranging from 10–20° at the stem to 6–26° at 50 cm from the stem. The angle increased with height in the crown to 39–50° at the stem and 64–76° at 50 cm from the stem at a level of 8.7 m. Branches were near vertical at the top of the tree (11.8 m). In more mature forests, branches at the base of the crown were often near vertical or pointed downwards under a low angle up to distances of 1 m from the stem after which the angle increased to 10–20°, pointing upwards (visual observations).

Figure 11.1D shows that the total mass of the trees increased roughly linearly with the height of the tree until just below the mid-crown position, after which it levelled off.

11.3.2 Wood Properties

Cown *et al.* (1983) provided information on the wood properties of *Pinus caribaea* trees grown in Fiji. The pines in Fiji produced medium to high density wood with an average basic density of 515 kg m^{-3} for trees at age 15 grown in the lowlands. The basic density was positively related to tree age and the largest increase in density was observed between age 5 and 12 (from 340 kg m^{-3} to 470 kg m^{-3}). The basic density showed a negative correlation with site elevation, with 15-year old trees grown above 300 m a.s.l. having an average basic density of 445 kg m^{-3}. The density was highest in stemwood at the base of the tree (540 kg m^{-3} at age 11–15) and dropped below 460 kg m^{-3} above a height of 8 m.

The average dry wood density measured during the present study increased slightly with forest age, from 440($\pm$40) kg m^{-3} in 7 year old pines (n= 5) to 460($\pm$50) kg m^{-3} in 12 (n= 5) and 16-year-old pines (n= 5). The corresponding fresh wood density decreased from 1000($\pm$40) kg m^{-3} at age 7 to 910($\pm$100) kg m^{-3} at age 16. The basic density averaged 470, 526 and 500 kg m^{-3} in stemwood at the base of 7, 12 and 16 year old trees respectively, whereas corresponding densities at the top of the tree averaged 370, 404 and 370 kg m^{-3}.

The mass ratio of dry to fresh stemwood increased with forest age from 0.47($\pm$0.05) (n= 5) at age 7 to 0.51($\pm$0.02) (n= 5) at age 12 and 0.52($\pm$0.07) (n= 5) at age 16. Slightly lower ratios were observed when branches and twigs were included (0.47, 0.50 and 0.51 respectively). Since sampling was restricted to the dry season the presence of a seasonal pattern could not be evaluated.

11.3.3 Properties of Foliage

The average dry weight of individual needle sets was related to height in the canopy but not to age of the tree, as shown in Figure 11.2. The lowest needle weights were observed at the crown base, ranging from 0.13($\pm$0.03) g (n= 5) in Korokula forest

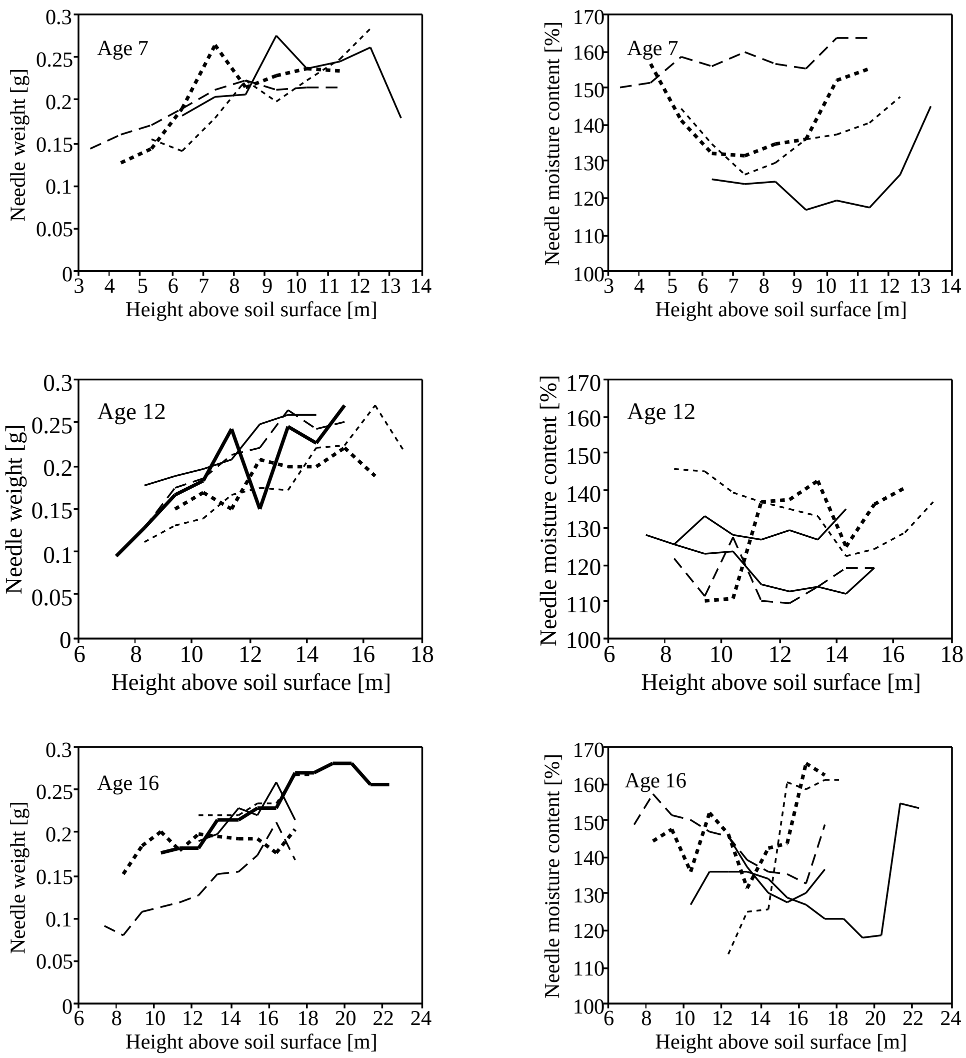


Figure 11.2: *Distribution of average dry weights and foliar moisture contents of individual needle sets (n= 100 needles m^{-1}) with height at age 7 (n= 4 trees), 12 (5 trees) and 16 (5 trees).*

to 0.17(±0.04) g (n= 5) in Koromani and Oleolega forest. Needle weights reached a maximum in the upper levels of the canopy (range 0.25(±0.04) – 0.26(±0.04) g) and decreased slightly at the top of the tree (range 0.222(±0.036) – 0.237(±0.03) g).

Needle moisture contents were related to needle age, as well as to soil moisture status at the time of sampling. Foliar moisture contents measured on 10 trees over a period of two years in a 10-year-old *Pinus caribaea* plantation forest in Toolara, Australia, decreased by 16–31% in old needles compared to the current growth. Similarly, needle moisture contents, measured during the wet season of 1991 in a 19-year-old forest near Darwin, Australia, decreased by 12–29% in old growth as compared to current growth. The moisture content of the current growth in Toolara varied between 137% and 161% over the 2-year period. A similar variation (133%–160%) was observed at the forest near Darwin (pers. comm. Dr. M.E. Alexander). During the present study observed needle moisture contents (Figure 11.2) varied between 110% and 170% of dry weight and were often lowest at the mid-crown position. The large variation observed between trees may partly be related to differences in soil moisture levels during sampling. The higher needle moisture contents observed in the lower levels of the canopy, where the oldest needles are usually found, reflects the regeneration of needles at this level due to improved light conditions following the defoliation by cyclone Sina and is therefore anomalous. The moisture content of the current growth (needles in the upper crown level) in Fiji showed a range similar to those observed in Australia.

Needles sampled in Tulasewa forest had an average length of 24.2(±2.7) cm (n= 146) and a total surface area of 21.05(±4.54) cm^2. The average weight of a dry needle set was 0.301 g resulting in a SLA of 3.55 m^2 kg^{-1}. Standard deviations could not be calculated as the weights of individual needle sets were not measured.

Needles collected at the base (8 m), the middle (13 m) and at the top (17 m) of the crown of tree C92 in Koromani forest were shorter than those collected in Tulasewa forest with average lengths ranging from 19.46(±2.1) cm (n= 30) at crown base to 20.0(±2.6) cm (n= 30) at mid-crown position. The average surface area of the Koromani needle sets increased from 16.1 cm^2 at the base of the crown to 19.0 cm^2 in the upper levels. The corresponding average needle weights increased from 0.15 g to 0.20 g (n= 100). The calculated SLA was 5.31 m^2 kg^{-1} at the base of the crown and decreased to 4.7 m^2 kg^{-1} and 4.9 m^2 kg^{-1} at a level of 13 m and at the top of the crown (17 m) respectively.

Needle lengths varied considerably with the position in the tree (visual observation by the author) but were roughly in the same range for the respective forest sites (*cf.* Figure 11.2) and the data obtained in the Tulasewa and Koromani forest plots were pooled to obtain and an average SLA of 3.77 m^2 kg^{-1}, which was subsequently used to calculate pre- and post-cyclone LAI values for each of the forest plots (Section 11.3.6).

11.3.4 Growth Rates

Tulasewa forest was vigorously growing during the wet season of 1990 with average diameter and height increments of 0.024(±0.007) m yr^{-1} (n= 18) and 2.5(±0.9) m yr^{-1} (n= 10) respectively. The growth slowed down somewhat during the dry season with mean diameter and height increments of 0.010(±0.008) m yr^{-1} (n= 6) and 1.5 m yr^{-1} (n= 8) respectively. This resulted in a pre-cyclone annual diameter increment of 0.018 m yr^{-1} and a height increment of 2.0 m yr^{-1}. The post-cyclone annual diameter increment was slightly lower at 0.014(±0.007) m yr^{-1} (n= 7) and was similar to the mean increments (n= 21) observed in a nearby permanent sample plot of the Fiji Pine Ltd. (0.017 m yr^{-1} and 0.016 m yr^{-1} during 1991 and 1992 respectively; pers. comm.

Dr. J.H.R. Heuch).

Average diameter increments in the Korokula forest plot were much lower than in the Tulasewa forest plot with values of 0.009(±0.005) m yr^{-1} (n= 10) for the wet season and 0.007(±0.004) m yr^{-1} (n= 10) for the dry season of 1990. This resulted in a mean annual pre-cyclone increment of 0.008(±0.003) m yr^{-1}. No increase (-0.001±0.005 m yr^{-1}) was observed between January 1991 and September 1991, *i.e.* after cyclone Sina, indicating that any biomass production was accounted for by regeneration of needles rather than wood production. However, post-cyclone mean annual diameter increments (n= 31) of 0.005 m yr^{-1} and 0.006 m yr^{-1} for 1991 and 1992 respectively were observed in a nearby permanent sample plot (pers. comm. Dr. J.H.R. Heuch).

The average diameter increment in Koromani forest was similar to that in Korokula forest at 0.013(±0.004) m yr^{-1} (n= 15) for the wet season and 0.007(±0.004) m $yr^{-}1$ (n= 15) for the dry season of 1990, resulting in a mean annual pre-cyclone increment of 0.009(±0.003) m yr^{-1}. As in Korokula forest, tree diameters showed no increase (-0.001±0.007 m yr^{-1}) between January 1991 and September 1991, although a post-cyclone annual diameter increment of 0.005 m yr^{-1} (n= 26) was again found in a nearby permanent sample plot of FPL (pers. comm. Dr. J.H.R. Heuch). Such reductions in diameter increment have also been observed to occur after pruning (50–70% of living crown removed) in an 8-year-old *Pinus patula* forest in Malawi (Adlard, 1969).

The increases in tree height fell within the error of measurements during the first six months of 1990, whereas cyclone damage resulted in an average decrease in tree height of 0.7(±1.5) m and 1.0(±1.9) m in Korokula and Koromani forest respectively.

11.3.5 Forest Structure

Table 11.1 provides information on the diameter, height, crown diameters and crown depth of trees in Tulasewa, Korokula and Koromani forests as measured at the start and end of the present study. Mean annual diameter increments (MAI) decreased with age from 0.026 m $year^{-1}$ in Tulasewa forest to 0.019 m yr^{-1} in Korokula forest and 0.014 m $year^{-1}$ in Koromani forest. Corresponding height increments decreased from 1.93 m $year^{-1}$ in Tulasewa forest to 1.34 m $year^{-1}$ and 1.17 m $year^{-1}$ in Korokula and Koromani forest respectively.

Crown depth increased only slightly after canopy closure from 9.1 m in Tulasewa forest to 11.1 m in Koromani forest. As such the living crown base level increased from an average 2.5 m above the soil surface at age 6 to an average 6.4 m above the soil surface at age 15. The crowns of the trees in Tulasewa forest were symmetrical and generally did not interlock although in some places overlap in foliage occurred. In Korokula forest tree crowns were interlocked and the unequal tree spacing resulted in asymmetrical crown shapes as indicated by the crown diameters which were on average 0.8 m larger between planting rows than within them. The tree crowns in Koromani forest were again symmetrical and interlocked in the better stocked areas of the plot. However, asymmetrical crowns were observed on trees along the edges of small gaps where trees had been removed by cyclones.

Changes in the distribution of *Dbhob*, tree height, crown diameter and crown depth over the period of a rotation are shown in Figures 11.3A–D. The frequency distribution curves of *Dbhob* (Figure 11.3A) approached normal distributions of which the mean increases with the age of the forest. The variation around the mean remained fairly constant during the development of the plantation.

In forests not affected by cyclones the shape of the tree height frequency distribution curves (Figure 11.3B) should be similar to that of the *Dbhob*. In the study

Table 11.1: *Averages and standard deviations of diameter, height, crown depth and crown diameter (m) of Pinus caribaea trees in the Tulasewa, Korokula and Koromani forest plots.*

	Average	SD	Maximum	Minimum	n
TULASEWA FOREST (Planted 1984)					
January 1990					
Dbhob	0.156	0.042	0.026	0.253	239
Height	11.6	2.3	15.8	3.6	239
Crown depth	9.1	2.3	14.4	2.1	239
Crown diameter	2.6	0.8	4.6	0.8	225
January 1990, trees planted in 1980					
Dbhob	0.255	0.038	0.182	0.315	15
Height	14.7	3.2	19.7	8.1	15
Crown depth	10.5	2.4	15.1	5.0	15
Crown diameter	3.7	0.9	5.0	2.0	15
September 1991					
Dbhob	0.181	0.044	0.277	0.045	135
Height	13.1	2.6	18	4.2	61
September 1991, trees planted in 1980					
Dbhob	0.272	0.044	0.339	0.185	14
Height	17.9	1.7	20.6	15.7	7
KOROKULA FOREST (Planted 1979)					
January 1990					
Dbhob	0.204	0.036	0.281	0.095	100
Height	14.7	2.6	19.1	6.0	100
Crown depth	9.7	2.2	15.1	4.6	100
Crown diameter (2 m)	3.0	1.2	9.0	0.2	99
Crown diameter (3 m)	3.8	0.9	7.0	1.6	99
September 1991					
Dbhob	0.211	0.038	0.306	0.100	95
KOROMANI FOREST (Planted 1975)					
January 1990					
Dbhob	0.249	0.055	0.461	0.114	100
Height	17.5	2.6	24.3	5.7	100
Crown depth	11.1	2.2	16.5	3.5	100
Crown diameter (3 m)	3.9	1.2	8.0	1.4	99
September 1991					
Dbhob	0.256	0.057	0.479	0.120	100

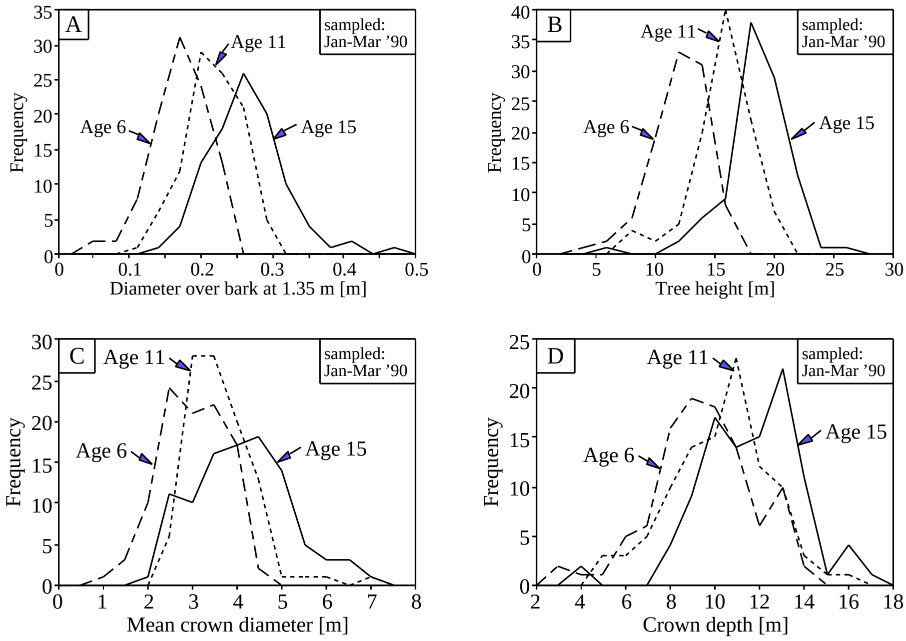


Figure 11.3: *Frequency distributions (n= 100) of the diameter at breast height (A), height (B), crown diameter (C) and crown depth (D) of Pinus caribaea trees at age 6, 11 and 15.*

forests in Fiji, however, the number of trees damaged by cyclones increased with age of the forest (0% in Tulasewa forest in 1990, 35% in Koromani forest). As a result the tree height distribution curves show an increased skewness to the left with increasing forest age (Figure 11.3B).

The crown diameter frequency distribution curves of Tulasewa forest and Koromani forest (Figure 11.3C), which both had been planted at a spacing of 3*3 m, had a different shape than that of Korokula forest (spacing 2*3 m), showing the influence of different spacings on crown development. In Koromani forest, and to a much lesser extent in Korokula forest, gaps were created as a result of cyclone damage. Trees at the edge of such gaps usually had larger crown diameters which showed up in the frequency distributions of these forests as a skewness to the right. Figure 11.3D shows the general increase in mean crown depth with forest age. The variation around the mean is high throughout the rotation.

11.3.6 Leaf Area Indices and Canopy Gap Fractions

For each forest plot pre- and post-cyclone LAIs were calculated by combining estimates of foliage biomass (Section 11.5.2) with the SLA (Section 11.3.3). The results are presented in Table 11.2. The pre-cyclone LAI was lowest in Tulasewa forest, whereas the highest value was found for Korokula forest, due to its higher stocking (compared to Koromani forest). Post-cyclone LAIs, measured some 6–9 months after the cyclone event, were significantly lower (α= 0.05) in spite of the regeneration of foliage that

Table 11.2: *Pre- and post-cyclone leaf area indices as obtained from foliage biomass estimates, and from PAR attenuation measurements (κ= 0.52). Standard deviations are given between parentheses, n represents the number of trees (biomass estimates) or the number of sampling locations (ceptometer estimates).*

Location	Pre-cyclone LAI Biomass [m2 m-2]	n	Pre-cyclone LAI Ceptometer [m2 m-2]	n	Post-cyclone LAI Biomass [m2 m-2]	n	Post-cyclone LAI Ceptometer [m2 m-2]	n
Tulasewa forest	3.5 (0.9)	239	3.7 (1.5)	50	1.7 (0.6)	135	1.5 (1.1)	60
Korokula forest	4.4 (0.7)	100			3.2 (0.7)	95	3.5 (1.4)	105
Koromani forest	4.0 (0.7)	100			3.1 (0.8)	100	2.4 (1.3)	74
Koromani meteosite North							4.0 (1.2)	65
Koromani meteosite South							3.0 (1.4)	66
Koromani meteosite							3.5 (1.4)	131

had occurred in the mean time.

LAI values were also calculated from PAR attenuation measurements (Pierce and Running, 1988) using the Beer-Lambert equation (Section 11.2). Below-canopy PAR values ranged between 3% and 74% of incoming PAR in Tulasewa forest, with an average of 20%. After the forest was damaged by cyclone Sina a larger range of 8%–85% was observed and the PAR within the forest averaged 39% of that outside the forest. Post-cyclone average values of below-canopy PAR in Korokula and Koromani forests ranged from 16–36% of incoming PAR. No pre-cyclone observations were made in these forests.

In Koromani forest post-cyclone ceptometer measurements were made in the forest plot as well as in the area surrounding the meteorological tower (Koromani meteosite). To the north of the road (Figure 3.3) the forest was denser than that to the south of the road which had sustained considerable damage from cyclones. This showed up neatly in the LAI values obtained for the two locations (Table 11.2). The large range in LAI values obtained for Koromani forest reflects the variation in the canopy as a result of cyclone damage.

The LAI values calculated from PAR attenuation measurements using the Beer-Lambert equation were within 25% of those obtained from the biomass and SLA measurements. Extinction coefficients could be calculated for the forest sites by combining the PAR attenuation values with the LAI values derived from biomass measurements. This resulted in κ values of 0.46 and 0.55 for the pre- and post-cyclone forest at Tulasewa, respectively, whereas post-cyclone values of 0.45 and 0.43 were obtained for Korokula and Koromani forests, respectively. These values are close to the average extinction coefficient of 0.52 found for coniferous forests in temperate climates (Jarvis *et al.*, 1976).

Post-cyclone canopy gap fractions ranged from a minimum of 27($\pm$22)% in the forest surrounding the meteorological tower in Koromani to 50($\pm$26)% in Tulasewa forest. The canopy gap fraction measured in Korokula forest was 28($\pm$23)%. Again there was a considerable variation of the canopy gap fraction in Koromani forest with a minimum of 19($\pm$16)% in the forest north of the road and a maximum of 46($\pm$26)% within the plot (*cf.* Section 6.4.1).

Table 11.3: *Regression constants (a, b), standard errors (SE) of the means, coefficients of determination and standard errors of estimate (ERE) for regression analyses using a multiplicative model ($h = a * Dbhob^b$) on two biomass data sets. The number of trees is represented by n.*

Dependent variable	a	SE	b	SE	R-squared	ERE	n
Sound trees	48.2787	1.0276	0.7295	0.0165	0.761	1.156	617
All trees	43.5496	1.0296	0.6832	0.0182	0.634	1.195	811

11.4 Estimations of Above-Ground Biomass

Several studies have been published dealing with the changes in above-ground biomass and nutrient content of *Pinus caribaea* plantation forests at various stages during a rotation. In these studies the whole-tree biomass and the biomass of the tree components (stemwood, stembark, branches and needles) are generally related to tree diameter (Egunjobi and Bada, 1979; Rance *et al.*, 1982; Kadeba, 1991) or volume, expressed as $Dbhob^2h$ (Egunjobi, 1976; , 1983) or as $0.5 * BA * h$, (Russell, 1983) where BA represents basal area (Rance *et al.*, 1982). Allometric regression models of the form $\ln Y = a + b \ln X$, where Y and X represent dependent and independent variables respectively, were used in these studies. Previous work on the determination of biomass of pine plantations in Fiji was carried out by Claeson *et al.* (1984), who compared four regression models on a data set of 18 trees. They found that the logarithmic model relating weight to volume ($Dbhob^2h$) showed the highest correlation coefficients. It is common to relate biomass to *Dbhob* only (Pardé, 1980) because the inclusion of h often does not improve the fit of the regression (Rance *et al.*, 1982; Claeson *et al.*, 1984). However, the inclusion of height in the regression equations does make sense in the Fiji situation, where the forests are often damaged by cyclones which results in a poor correlation between *Dbhob* and h for damaged trees. To illustrate this, diameter-height relations were established using data collected at Tulasewa, Korokula and Koromani forests. The data set consisted of 811 trees of which 194 were damaged by cyclones. Regression analysis was performed on the whole data set, and on a smaller data set containing sound trees only (n= 617). A multiplicative model ($h = a * Dbhob^b$) gave the best fit with a coefficient of determination (r^2) of 0.76 for the sound tree data set. The coefficient of determination decreased to 0.63 when damaged trees were included. The results of the regression analyses and the calculated regression lines are shown in Table 11.3 and Figure 11.4 respectively. The inclusion of cyclone damaged trees resulted in a 6% decrease in predicted tree height.

The tree biomass data collected during the present study in Nabou forest are given in Table 11.4. They were consequently combined with those collected by Claeson *et al.* (1984) (summarized in Table 11.5) to obtain a data set of 32 trees for which expressions were obtained for the total tree biomass and for the mass of the bole, stemwood, stembark and branches. Because Claeson *et al.* (1984) did not make a distinction between branches and twigs, expressions for these components were obtained from the data collected during the present study (15 trees) only.

A logarithmic model ($\ln Y = a + b \ln X$) was used for biomass estimations, where Y represented the weight of the tree or its components and X the volume ($Dbhob^2h$).

Table 11.4: *Biomass data collected during the present study in the Tulasewa (A), Korokula (B) and Koromani forest plots (C), and in the Oleolega (O) catchment. All weights represent oven-dry values.*

Tree	Dbhob [m]	Height [m]	Total [kg]	Stem [kg]	Bole [kg]	Bark [kg]	Branches [kg]	Needles [kg]
A32	0.178	12.0	63.6	47.2	38.9	8.3	8.6	7.7
A47	0.188	12.3	83.0	60.8	50.4	10.4	13.9	8.2
A126	0.197	13.8	108.1	85.0	70.4	14.5	11.8	11.2
A141	0.189	11.8	92.5	55.1	47.5	7.6	19.5	16.4
A221	0.192	11.3	99.4	63.2	53.7	9.4	21.9	12.5
B17	0.206	14.4	125.7	98.3	83.8	14.5	18.2	8.9
B32	0.225	15.7	159.1	123.9	106.6	17.4	24.7	9.5
B59	0.212	16.2	138.4	111.6	100.1	11.5	17.9	8.7
B80	0.206	17.3	162.9	131.6	114.7	17.0	21.3	9.7
B92	0.210	15.8	150.9	113.3	99.9	13.4	26.1	11.4
C20	0.259	17.7	191.3	163.6	135.6	28.0	19.0	8.7
C88	0.270	17.9	225.9	176.5	152.4	24.1	32.9	16.0
C98	0.267	17.8	265.4	208.4	189.6	18.8	40.4	15.7
O13	0.260	18.7	225.5	185.7	163.3	22.4	27.2	12.3
O14	0.264	20.3	377.6	290.0	261.1	28.9	59.8	27.7

Tree	Dbhob [m]	Height [m]	D. branch [kg]	L. branch [kg]	D. twigs [kg]	L. twigs [kg]	Cones [kg]	M. flowers [kg]
A32	0.178	12.0	0.6	6.6	0.38	1.00	0.01	0.00
A47	0.188	12.3	1.8	10.9	0.53	0.71	0.09	0.00
A126	0.197	13.8	1.3	9.0	0.29	1.25	0.08	0.00
A141	0.189	11.8	2.3	14.8	0.56	1.74	1.50	0.00
A221	0.192	11.3	2.6	17.2	0.70	1.35	1.52	0.00
B17	0.206	14.4	3.3	13.7	0.23	0.94	0.16	0.00
B32	0.225	15.7	6.3	15.6	0.44	2.39	0.86	0.01
B59	0.212	16.2	2.9	13.9	0.32	0.74	0.13	0.04
B80	0.206	17.3	5.7	14.4	0.39	0.82	0.09	0.01
B92	0.210	15.8	4.2	18.4	0.81	2.68	0.00	0.00
C20	0.259	17.7	5.3	12.7	0.13	0.83	0.02	0.00
C88	0.270	17.9	2.4	26.4	0.46	3.72	0.15	0.00
C98	0.267	17.8	7.0	30.6	0.75	1.98	0.67	0.03
O13	0.260	18.7	3.5	22.4	0.21	1.12	0.22	0.00
O14	0.264	20.3	4.7	51.7	0.87	2.59	0.13	0.00

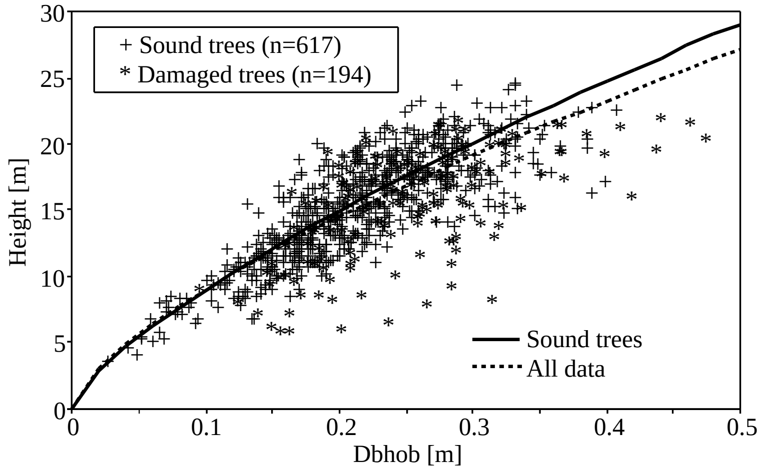


Figure 11.4: *Relationships between diameter at breast height and tree height for two data sets.*

Table 11.5: *Biomass data collected by Claeson* et al. *(1984) in the forests of the Fiji Pine Commission. One small tree ommited as its height (0.9 m) did not correspond with its diameter at breast height (0.04 cm). All weights expressed as oven-dry (105° C) weights.*

Tree	Dbhob [m]	Height [m]	Total [kg]	Stem [kg]	Bole [kg]	Bark [kg]	Branches [kg]	Needles [kg]
F67	0.230	17.2	189.0	145.2	132.4	12.8	18.0	16.7
P70	0.168	15.0	77.5	54.8	47.2	7.6	14.1	8.6
P73A	0.187	13.9	87.9	56.6	44.4	12.2	18.6	12.7
P78A	0.143	7.7	32.3	22.6	18.9	3.7	3.5	6.2
P68A	0.245	18.3	237.0	187.0	153.1	33.9	27.6	22.4
P68B	0.230	16.8	219.0	177.9	152.5	25.4	32.9	8.2
P69	0.179	16.8	140.2	107.3	95.4	11.9	19.5	13.4
P70	0.226	20.1	227.4	184.6	168.8	15.8	27.9	14.9
P71	0.171	10.8	52.9	34.9	28.1	6.8	4.8	13.7
P72	0.197	14.3	110.6	81.5	70.4	11.1	18.1	11.0
P73B	0.165	13.6	93.4	62.4	53.3	9.1	13.2	17.8
P74A	0.205	12.4	96.2	61.8	53.2	8.6	17.4	17.0
P74B	0.204	13.9	125.1	89.5	77.7	11.8	16.6	19.0
P75	0.179	11.6	69.7	49.8	43.1	6.7	7.1	12.8
P76	0.155	8.7	61.8	31.7	26.8	4.9	16.9	13.2
P77	0.125	6.8	37.4	22.6	19.6	3.0	5.4	9.4
P78	0.072	4.6	10.2	3.2	2.5	0.7	2.3	4.7

Table 11.6: *Regression constants (a, b), coefficients of determination (R-squared) and standard errors of estimate (ERE) for equations of the model* $\ln Y = a + b \ln X$ *to predict various biomass components of pinus caribaea trees in Viti Levu. The number of trees used in the regressions is represented by n.*

Dependent variable	a	SE	b	SE	R-squared	ERE	n
Total weight	5.2672	0.0391	0.8449	0.0372	0.945	1.19	32
Bole weight	5.0528	0.0373	1.0414	0.0355	0.966	1.18	32
Stemwood weight	4.9146	0.0419	1.0669	0.0398	0.960	1.20	32
Bark weight	2.9826	0.0427	0.8923	0.0406	0.942	1.21	32
Branch weight	3.2691	0.0799	0.7364	0.0759	0.758	1.42	32
Dead branch weight	1.3909	0.1601	0.9036	0.2927	0.423	1.67	15
Live branch weight	3.0400	0.1083	0.8073	0.1981	0.561	1.41	15
Dead twig weight	-0.9176	0.1754	-0.1302	0.3206	0.013	1.75	15
Live twig weight	0.4659	0.1585	0.4510	0.2898	0.157	1.66	15
Foliage							
Pre-cyclone	2.8143	0.1019	0.3105	0.0768	0.505	1.34234	18
Post-cyclone	2.5472	0.0878	0.4726	0.1698	0.392	1.32416	14

No corrections were made for the small errors resulting from the log-antilog transformation of the variables as these tend to increase the bias (Madgwick, 1983). The regression constants and the coefficients of determination are given in Table 11.6. The correlations between $Dbhob^2h$ and weight were good for total tree mass, bole, stemwood, stembark and combined branch and twig mass, with coefficients of determination ranging between 0.76 and 0.97. Tree biomass and predicted biomass have been plotted against *Dbhob* in Figure 11.5. The coefficients of determination were much lower (0.16–0.56) for the equations predicting biomass of foliage, dead and live branches and live twigs (table 11.6).

Fourteen of the 15 trees in the present data set were sampled within four to ten months after cyclone Sina defoliated the forests. Although fresh needles appeared shortly after the event, regeneration of foliage had not yet been completed at the time of sampling. This is clearly shown in Figure 11.6 where the foliage weights found during the present study and those of Claeson *et al.* (1984) are plotted against *Dbhob*. Separate regression equations were therefore obtained to predict pre-cyclone needle biomass (using the data set of Claeson *et al.* (1984) and tree A141 from the present data set) and post-cyclone needle biomass (using the present data set excluding tree A141) as shown in Figure 11.6. Because cyclones occur regularly in Fiji (*cf.* Section 2.4.4), the forests may be defoliated several times during a rotation and foliage mass may show large variations between trees within an even-aged cyclone damaged stand, as already indicated by the variations in the LAI for Koromani forest (Section 11.3.6).

No correlation with volume was observed for dead twigs ($r^2 = 0.01$) and the average weight of dead twigs on the five trees in each age class was used to calculate the total dead twig biomass for each plot.

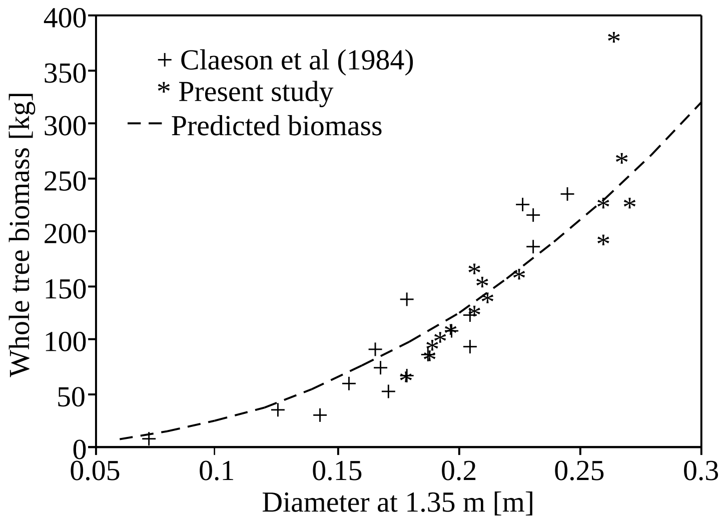


Figure 11.5: *Observed and predicted whole tree biomass as calculated with the logarithmic model. The predicted biomass curve was calculated using heights obtained from the diameter-height expression for the sound tree data set.*

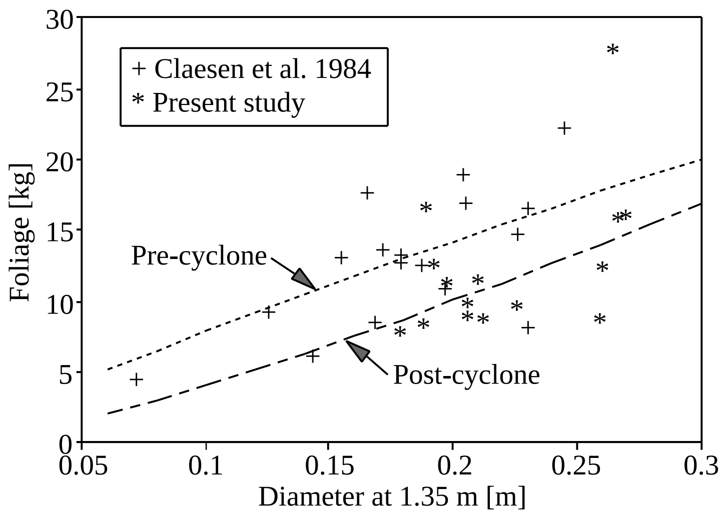


Figure 11.6: *Observed and predicted pre- and post-cyclone foliage biomass.*

11.5 Forest Biomass and Nutrient Content

The rate of nutrient accumulation by a plantation forest is a function of the rate of biomass production, the development stage of the plantation, the availability of nutrients in the soil and the tree species (Miller, 1984). Due to the length of a rotation period (15–20 years) it is usually not feasible to monitor a forest in this respect from planting until harvesting. Alternatively, information on the accumulation of biomass and nutrients may be obtained using a false time series, provided that environmental factors (particularly soils) are similar for each of the study forests (Bruijnzeel, 1983a). This approach has been used during the present study. Therefore the biomass and nutrient accumulation in pine forests of age 6, 11 and 15, representing young, intermediate and mature forest, respectively, were determined.

The research plots were located in relatively well stocked areas within Tulasewa, Korokula and Koromani forests (*cf.* Sections 3.2 – 3.4). The biomass in each of the plots was calculated from the regression equations and growth rates given in the previous sections and results are given in Section 11.5.1. The biomass of the mature forest stand in the Oleolega catchment was calculated from the volume of wood harvested from the catchment between December 1990 and August 1991 and will be discussed separately in Section 15.2.1.

To assess the impact of differences in the soil nutrient status on forest nutrient content an attempt was made to relate nutrient concentrations in foliage and stemwood (Section 11.5.2) to those in the soil around the trees sampled for biomass (Section 11.5.3). The nutrient content and rate of uptake for each forest site will be discussed in Section 11.5.4.

11.5.1 Standing Biomass and Increment Rates

Pine Biomass

Details on the above-ground living pine biomass of the pine trees at the Tulasewa, Korokula and Koromani forest plots, the distribution of biomass within the trees and the productivity of the respective forests are given in Table 11.7. In January 1990 utilisable wood (stemwood and bark) accounted for 70% of the total biomass in Tulasewa forest, with branches and foliage each accounting for 15% of the total biomass. The proportion of needle biomass decreased with forest age to 11% of the pine biomass in the Korokula forest plot and to 7% of that in the Koromani forest plot. This corresponded with an increase in the proportion of utilizable wood to 75% and 80% of the pine biomass in the Korokula and Koromani forest plots, respectively. The proportion of branches and twigs remained more or less constant at 12–13%. Bark accounted for 14% (Tulasewa) to 12% (Koromani) of the total stem mass.

To obtain estimates of pre-cyclone forest productivity and of the loss of biomass after the passage of cyclone Sina, the above-ground biomass for January 1991 was predicted using pre-cyclone *Dbhob* and h increments (Section 11.3.4). Biomass predictions were made for sound as well as for cyclone damaged forests using the appropriate regression equations for the prediction of foliar biomass (Table 11.6). The loss of above-ground living biomass resulting from cyclone damage was calculated as the difference between the predicted biomass for the sound forest (using pre-cyclone diameter and height increments given in Section 11.3.4) and that for the damaged forest in January 1991 (based on the decrease in stocking, post-cyclone growth rates, and using the appropriate regression constants for foliage biomass). Tulasewa forest experienced a loss

Table 11.7: *Actual and predicted biomass and annual productivity estimates (MAI up to January 1990) for Tulasewa, Korokula and Koromani forests in kg ha^{-1} dry weight.*

	Total	Stemwood	Stembark	Branches Dead	Branches Live	Twigs Dead	Twigs Live	Needles Dead	Needles Live	Cones
TULASEWA FOREST, ACTUAL BIOMASS										
Jan '90	62245	37129	6220	1254	7102	407	767		9366	
% of total		59.6	10.0	2.0	11.4	0.7	1.2		15.0	
Sep '91	54522	36329	5621	1139	6171	238	563	73	4460	206
% of total		66.6	10.3	2.1	11.3	0.4	1.0	0.1	8.2	0.4
KOROKULA FOREST, ACTUAL BIOMASS										
Jan '90	109400	71181	10935	2217	11941	360	1050		11715	
% of total		65.1	10.0	2.0	10.9	0.3	1.0		10.7	
Sep '91	103326	69577	10637	2157	11588	342	1009	124	8016	203
% of total		67.3	10.3	2.1	11.2	0.3	1.0	0.1	7.8	0.2
KOROMANI FOREST, ACTUAL BIOMASS										
Jan '90	144800	101579	13980	2855	14485	301	1028		10572	
% of total		70.2	9.7	2.0	10.0	0.2	0.7		7.3	
Sep '91	143283	101993	14013	2862	14508	301	1028	162	8268	148
% of total		71.2	9.8	2.0	10.1	0.2	0.7	0.1	5.8	0.1
TULASEWA FOREST, PREDICTED BIOMASS JAN '91										
Sound forest	84741	53294	8469	1713	9418	407	905		10535	
% of total		62.9	10.0	2.0	11.1	0.5	1.1		12.4	
Cyclone damaged	49697	32761	5152	1043	5703	238	539		4261	
% of total		65.9	10.4	2.1	11.5	0.5	1.1		8.6	
KOROKULA FOREST, PREDICTED BIOMASS JAN '91										
Sound forest	116969	76833	11665	2367	12664	360	1086		11993	
% of total		65.7	10.0	2.0	10.8	0.3	0.9		10.3	
Cyclone damaged	101048	67852.1	10422.9	2113.4	11380	342.2	1000		7937.4	
% of total		67.1	10.3	2.1	11.3	0.3	1.0		7.9	
KOROMANI FOREST, PREDICTED BIOMASS JAN '91										
Sound forest	154392	109030	14849	3034	15305	301	1062		10811	
% of total		70.6	9.6	2.0	9.9	0.2	0.7		7.0	
Cyclone damaged	143903	102645	14112	2882	14612	301	1034		8318	
% of total		71.3	9.8	2.0	10.2	0.2	0.7		5.8	
PRODUCTIVITY OF TULASEWA FOREST										
CAI (1990)	22496	16165	2249	459	2316	0	138		1169	
MAI (1990)	10374	6188	1037	209	1184	68	128		1561	
Loss by cyclone	35044	20533	3317	670	3715	169	366		6274	
PRODUCTIVITY OF KOROKULA FOREST										
CAI (1990)	7569	5651	730	150	723	0	36		278	
MAI (1990)	9945	6471	994	202	1086	33	95		1065	
Loss by cyclone	15921	8981	1242	254	1284	18	86		4056	
PRODUCTIVITY OF KOROMANI FOREST										
CAI (1990)	9592	7451	869	179	820	0	34		239	
MAI (1990)	9653	6772	932	190	966	20	69		705	
Loss by cyclone	10489	6385	737	152	693	0	28		2493	

in living biomass of 35,044 kg ha^{-1} (or 41% of the pre-cyclone above-ground biomass) of which 68% was accounted for by utilisable wood. Defoliation caused a reduction of 60% in the needle biomass of the remaining trees, lowering the proportion of the foliage biomass from 15% of the total in January 1990 to 8% in September 1991. The decrease in stocking from 826 stems ha^{-1} to 485 stems ha^{-1} resulted in a net loss in above-ground tree biomass of 7723 kg ha^{-1} at Tulasewa during the study. The tree biomasses in the Korokula and Koromani forest plots were reduced by 15,921 kg ha^{-1} and 10,489 kg ha^{-1} respectively. In Korokula forest the needle biomass was reduced by 34% causing a decrease in the proportion of needle mass to the total biomass from 11% to 8%. The cyclone caused an estimated reduction of 23% in the needle biomass of Koromani forest.

The stocking in Korokula forest was reduced from 822 stems ha^{-1} to 781 stems ha^{-1} by cyclone Sina and this, in combination with a decrease in average tree height, resulted in a loss in above-ground tree biomass of 6074 kg ha^{-1} during the study. The cyclone defoliated Koromani forest for a large part and afflicted some damage to tree tops but the stocking remained equal at 621 stems ha^{-1}. As the damage was limited to the forest canopy a small net loss in above-ground tree biomass of 1517 kg ha^{-1} was observed during the study.

The mean annual increment (MAI) of total pine biomass decreased slightly with forest age from 10374 kg ha^{-1} in the Tulasewa forest plot to 9653 kg ha^{-1} in the Koromani forest plot. Current annual increases in biomass components (CAI) for 1990 (Table 11.7) were calculated as the difference in above-ground living biomass as measured in January 1990 and predicted (from growth rate measurements given in Section 11.3.4) for sound forest in January 1991. Tulasewa forest was estimated to have accumulated biomass at the highest rate in 1990 with a CAI of 22496 kg ha^{-1} of which 18414 kg ha^{-1}, or 82%, was used for the production of utilisable wood. The CAI of foliage was lower than the MAI, indicating that crown development had peaked at an earlier age. The converse was true for the production of woody material for which the CAI was 2–2.6 times as large as the MAI. The CAI values for all tree components in the Korokula and Koromani forest plots were lower than the corresponding MAI values, indicating that maximum biomass production had occurred earlier in the rotation. Harvestable wood production accounted for 84% and 87% of the CAI in Korokula and Koromani forests respectively.

Undergrowth Biomass

No attempt was made to measure biomass of the living undergrowth directly in Tulasewa forest due to its large seasonal variation (grass). However, a rough estimate was obtained by multiplying the amount of undergrowth litter present on the forest floor in the Tulasewa forest plot (Section 12.5) times the mean ratio (1.23) of grass biomass to grass litter standing crop at the Nabou grassland site grassland (1.20, May 1991) and in Koromani forest (1.26, May 1991). This resulted in an estimated undergrowth biomass of 8066 kg ha^{-1}, which is comparable to that observed in the grassland (Section 10.3).

The undergrowth biomass of Korokula forest was estimated in a similar fashion, resulting in a low value of 1550 kg ha^{-1}. This value may be caused by the low amounts of light penetrating the forest, as indicated by the low canopy gap fractions obtained earlier for this forest (Section 11.3.6).

The undergrowth biomass in the Koromani forest plot was measured and amounted to 3296($\pm$736) kg ha^{-1}, of which some 43% consisted of non-seasonal scrubs (*e.g. Psid-*

Table 11.8: *Average nutrient concentrations and standard deviations (SD) in various tree components in Tulasewa forest. Concentrations of macronutrients are in % and those of micronutrients are in ppm.*

Nutrient	Stemwood	Stembark	Branches Dead	Branches Live	Twigs Dead	Twigs Live	Needles Dead	Needles Lower	Needles Middle	Needles Upper	Needles Avg	Whole Tree
N	0.095	0.181	0.082	0.178	0.138	0.373	0.306	0.832	0.897	0.995	0.908	0.218
SD	*0.029*	*0.065*	*0.018*	*0.033*	*0.026*	*0.059*	*0.029*	*0.134*	*0.062*	*0.147*	*0.084*	*0.046*
P	0.015	0.020	0.007	0.027	0.011	0.089	0.024	0.078	0.092	0.112	0.094	0.026
SD	*0.001*	*0.007*	*0.002*	*0.003*	*0.005*	*0.035*	*0.008*	*0.011*	*0.020*	*0.024*	*0.015*	*0.003*
K	0.067	0.098	0.027	0.146	0.032	0.367	0.108	0.384	0.425	0.594	0.454	0.130
SD	*0.018*	*0.024*	*0.013*	*0.022*	*0.022*	*0.089*	*0.021*	*0.078*	*0.080*	*0.137*	*0.060*	*0.020*
Ca	0.048	0.052	0.144	0.113	0.186	0.178	0.732	0.699	0.518	0.292	0.507	0.127
SD	*0.004*	*0.010*	*0.015*	*0.024*	*0.015*	*0.021*	*0.215*	*0.122*	*0.146*	*0.110*	*0.093*	*0.029*
Mg	0.022	0.040	0.048	0.067	0.083	0.120	0.218	0.233	0.210	0.185	0.208	0.056
SD	*0.004*	*0.005*	*0.010*	*0.012*	*0.016*	*0.014*	*0.065*	*0.052*	*0.033*	*0.029*	*0.031*	*0.008*
B							10.7	10.5	8.4	8.1	9.0	
SD							*1.7*	*2.3*	*1.8*	*2.3*	*1.6*	
Mn							801	586	591	410	558	
SD							*391*	*282*	*132*	*176*	*107*	
Zn							30	33	34	32	33	
SD							*7*	*6*	*10*	*16*	*9*	

ium guajava, 36%) and young trees (*e.g. Commersonia echinata*, 7%). Grasses (*e.g. Pennisetum polystachyon*) accounted for only 37%, indicating that the undergrowth composition had changed considerably during a rotation.

Increased litter production by the undergrowth after the cyclone event in November 1990 (Section 12.3.1) in the Tulasewa and Korokula forest plots suggested that the improved light conditions within the stands (Section 11.3.6) caused an increase in productivity of the undergrowth. No such increase was observed in the Koromani forest plot.

11.5.2 Nutrient Concentrations of Pine Trees

Average nutrient concentrations and standard deviations (n= 5) for tree components and whole trees in Tulasewa and Korokula forests are given in Tables 11.8 and 11.9 respectively. Because there were no significant differences (α= 0.05) between concentrations in the components of trees sampled in the Koromani forest plot (n= 3) and in the Oleolega catchment (n= 2) the data were pooled and the results are shown in Table 11.10. There was considerable variation in nutrient concentrations between tree components. Concentrations of N, P and K generally increased in the following order: stemwood, dead branches, dead twigs < live branches, bark < dead needles, live twigs < live needles, whereas the concentrations of Ca and Mg showed a different pattern and increased in the order stemwood, bark < dead branches, live branches < dead twigs, live twigs < live needles < dead needles.

Even within an even-aged stand considerable variation was observed in the nutrient concentrations of all components. The largest variations were generally observed for P and K. Such variations in nutrient concentrations were also observed within even-aged *Pinus patula* stands in Tanzania (Lundgren, 1978).

Table 11.9: *Average nutrient concentrations and standard deviations (SD) in various tree components in the Korokula forest plot. Concentrations of macronutrients are in % and those of micronutrients are in ppm.*

Nutrient	Stemwood	Stembark	Branches Dead	Branches Live	Twigs Dead	Twigs Live	Needles Dead	Needles Lower	Needles Middle	Needles Upper	Needles Avg	Whole Tree
N	0.072	0.156	0.086	0.141	0.156	0.508	0.491	0.882	0.980	1.054	0.965	0.150
SD	*0.020*	*0.031*	*0.012*	*0.020*	*0.032*	*0.219*	*0.055*	*0.079*	*0.089*	*0.158*	*0.097*	*0.020*
P	0.016	0.069	0.016	0.019	0.020	0.080	0.031	0.065	0.069	0.073	0.068	0.026
SD	*0.010*	*0.064*	*0.019*	*0.019*	*0.005*	*0.046*	*0.007*	*0.009*	*0.003*	*0.007*	*0.005*	*0.007*
K	0.039	0.051	0.022	0.077	0.025	0.318	0.082	0.340	0.323	0.366	0.338	0.066
SD	*0.007*	*0.016*	*0.005*	*0.004*	*0.015*	*0.109*	*0.025*	*0.081*	*0.069*	*0.129*	*0.073*	*0.012*
Ca	0.052	0.073	0.138	0.120	0.236	0.231	0.642	0.553	0.423	0.274	0.414	0.091
SD	*0.008*	*0.038*	*0.040*	*0.056*	*0.033*	*0.091*	*0.184*	*0.287*	*0.146*	*0.057*	*0.198*	*0.019*
Mg	0.024	0.047	0.047	0.062	0.085	0.176	0.305	0.296	0.283	0.274	0.291	0.049
SD	*0.003*	*0.012*	*0.009*	*0.017*	*0.011*	*0.106*	*0.082*	*0.095*	*0.079*	*0.071*	*0.068*	*0.006*
B							13.8	12.6	11.6	12.1	12.2	
SD							*2.6*	*2.9*	*1.9*	*4.6*	*2.4*	
Mn							357	358	289	211	298	
SD							*57*	*105*	*25*	*20*	*51*	
Zn							23	25	29	34	29	
SD							*9*	*11*	*8*	*9*	*8*	

Table 11.10: *Average nutrient concentrations and standard deviations (SD) in various tree components in the Koromani forest plot and in the Oleolega catchment. Concentrations of macronutrients are in % and those of micronutrients are in ppm.*

Nutrient	Stemwood	Stembark	Branches Dead	Branches Live	Twigs Dead	Twigs Live	Needles Dead	Needles Lower	Needles Middle	Needles Upper	Needles Avg	Whole Tree
N	0.073	0.171	0.104	0.134	0.150	0.435	0.411	1.017	1.027	1.093	1.041	0.151
SD	*0.017*	*0.042*	*0.027*	*0.014*	*0.018*	*0.042*	*0.070*	*0.121*	*0.109*	*0.128*	*0.106*	*0.023*
P	0.010	0.014	0.008	0.015	0.009	0.058	0.029	0.066	0.067	0.077	0.070	0.014
SD	*0.004*	*0.006*	*0.004*	*0.001*	*0.004*	*0.008*	*0.014*	*0.008*	*0.011*	*0.017*	*0.010*	*0.003*
K	0.049	0.088	0.039	0.097	0.038	0.347	0.095	0.405	0.412	0.667	0.488	0.087
SD	*0.008*	*0.045*	*0.006*	*0.019*	*0.024*	*0.082*	*0.018*	*0.062*	*0.098*	*0.270*	*0.116*	*0.020*
Ca	0.061	0.114	0.160	0.154	0.291	0.320	0.761	0.690	0.578	0.331	0.533	0.108
SD	*0.012*	*0.060*	*0.046*	*0.059*	*0.033*	*0.100*	*0.050*	*0.163*	*0.135*	*0.099*	*0.117*	*0.019*
Mg	0.020	0.038	0.033	0.046	0.058	0.123	0.178	0.173	0.162	0.161	0.173	0.038
SD	*0.003*	*0.014*	*0.005*	*0.009*	*0.006*	*0.030*	*0.044*	*0.033*	*0.045*	*0.043*	*0.041*	*0.012*
B							14.7	16.0	13.6	14.9	14.8	
SD							*1.3*	*3.4*	*2.3*	*4.3*	*2.6*	
Mn							486	872	827	482	741	
SD							*200*	*703*	*786*	*613*	*608*	
Zn							26	29	32	35	32	
SD							*4*	*6*	*7*	*9*	*7*	

Foliar nutrient levels varied with position in the crown. Concentrations of N, P, K and Zn increased with height and were lowest in dead needles, indicating that retranslocation of these nutrients into living tissue may occur prior to abscission. Concentrations of Ca, Mg, B and Mn decreased with height (needle age) and were highest in dead foliage indicating accumulation of these nutrients in litterfall. Micronutrients were not analyzed in woody components and estimates of the amount of micronutrients in stem biomass were therefore made using the average concentrations of B, Mn and Zn observed in 12 stems sampled in the Oleolega drainage basin (Table 15.2).

Significance levels for the differences in average nutrient concentrations between sites are shown in Table 11.11. Significant differences between the sites were observed for all nutrients except Zn (in foliage only). Egunjobi and Bada (1979) observed little variation in nutrient concentrations in *Pinus caribaea* tree components between two stands of age 6 and 10 planted on soils with similar chemical characteristics in Nigeria. This suggests that the presently observed differences in nutrient concentrations between the sites may be related to differences in soils rather than to changes with forest age. Therefore, an attempt is made in Section 11.5.3 to relate differences in nutrient concentrations of tree components to differences in soil nutrient status. The impact of inter-site differences in nutrient concentrations in the major nutrients sinks (such as stemwood and foliage) on the prediction of nutrient accumulation during a rotation period will be discussed in Section 11.5.4.

11.5.3 Plant–Soil Relations

The nutrient content of a forest depends on the accumulation of biomass and the nutrient concentrations in the various tree components, which are both in some way related to soil properties.

It is unlikely that the first rotation forests in the Nabou Estate have experienced nutrient or water stress for long periods of time. Therefore the impact of differences in soil type on biomass accumulation may be considered relatively small when compared to the impact of cyclones. However, differences in chemical properties of the soils in Tulasewa, Korokula and Koromani forests (Chapter 4) may well have influenced concentrations of nutrients in the various tree components (Mead, 1984), and thereby overall forest nutrient content.

To complicate the matter, the uptake of any specific nutrient often not only depends on the availability of that nutrient in the soil but also on a range of other factors like soil pH, the presence of other nutrients or complexes which interact with the nutrient under consideration, soil environmental conditions (*e.g.* moisture conditions, structure) and biotic factors (*e.g.* presence of fungi, distribution of roots) (Mead, 1984; Turner and Lambert, 1986). As such it is difficult to predict how variations in soil nutrient status will affect the total nutrient content of a forest at the end of the rotation.

Linear regression analysis was used to see whether stemwood and foliar nutrient levels (weighted averages) of the 15 trees sampled for biomass could be related to corresponding nutrient levels and pH_{H2O} in the 0–20 cm layer of soil around each of these trees. No attempts were made to relate nutrient levels in bark and branches to those in the soil as these tree components contained only a minor part of the total tree nutrient content (Tables 11.14 – 11.16). The regression equations used were of the form $Y = a_1X_1 + a_2X_2 + b$ where Y represented the levels of N, P, K, Ca, Mg in the tree components, and X_1 and X_2 those of corresponding nutrients in the soil and, whenever included in the regression, pH_{H2O}. No data were available for the micronutrient

Table 11.11: *Significance levels for differences in average nutrient concentrations in tree components per site. A= Tulasewa forest, B= Korokula forest, CO= Koromani/Oleolega forest.*

Difference	**Stem**		**Branches**		**Twigs**		**Foliage**			
in means	wood	bark	Dead	Live	Dead	Live	Dead	Low	Mid	High
NITROGEN										
A<>B	ns	ns	ns	>*	ns	ns	<***	ns	<*	ns
A<>CO	ns	ns	ns	>**	ns	<*	<**	<**	<**	ns
B<>CO	ns	ns	ns	ns	ns	ns	>*	<*	ns	ns
PHOSPHORUS										
A<>B	ns	<*	ns	>**	ns	ns	ns	>**	>**	>***
A<>CO	ns	<*	>*	>*	>***	ns	>*	>**	>**	>**
B<>CO	>*	ns	ns	ns	ns	ns	ns	ns	ns	ns
POTASSIUM										
A<>B	>***	>***	ns	>***	ns	ns	ns	ns	>**	>**
A<>CO	>*	ns	<*	>***	ns	ns	ns	ns	ns	ns
B<>CO	<*	<*	<***	<*	ns	ns	ns	ns	<*	<**
CALCIUM										
A<>B	ns	ns	ns	ns	<*	ns	ns	ns	ns	ns
A<>CO	<**	<**	ns	<**	<***	<**	ns	ns	ns	ns
B<>CO	ns	ns	ns	<*	ns	ns	ns	ns	<*	ns
MAGNESIUM										
A<>B	ns	ns	ns	ns	ns	ns	ns	ns	<*	<**
A<>CO	ns	ns	>**	>**	>***	ns	ns	>**	>*	ns
B<>CO	>*	ns	>**	>**	>**	ns	>**	>**	>**	>**
ZINC										
A<>B							ns	ns	ns	ns
A<>CO							ns	ns	ns	ns
B<>CO							ns	ns	ns	ns
MANGANESE										
A<>B							>**	>*	>***	>**
A<>CO							ns	ns	ns	ns
B<>CO							ns	<*	ns	ns
BORON										
A<>B							<*	ns	<**	<*
A<>CO							<**	<**	<***	<**
B<>CO							ns	<*	ns	ns

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

Table 11.12: *Regression constants (a_1, a_2 and b) and coefficients of determination for regression equations relating foliage and stem nutrient concentrations (%) to corresponding exchangeable nutrient concentrations in the soil (meq 100 g^{-1} soil) and pH_{H2O}.*

Dependent Y	Independent X1	X2	Regression constants a1	a2	b	CD	n
Stemwood							
K	K		0.243		0.031	0.341	15
K	K	pH	0.219	-0.017	0.126	0.385	15
P	pH		0.012		-0.048	0.128	15
P	P-Bray		0.257		0.008	0.586	3
Ca	pH		-0.015		0.135	0.100	15
Mg	pH		0.005		-0.006	0.107	15
Foliage							
K	K		1.288		0.316	0.204	15
K	K	pH	1.045	-0.176	1.275	0.301	15
N	pH		-0.179		1.924	0.102	15
P	P-Bray		-0.501		0.087	0.254	3
P	pH		-0.028		0.226	0.116	15
Ca	pH		-0.307		2.127	0.159	15
Mg	pH		0.167		-0.667	0.223	15
Mn	pH		-1004		5897	0.243	15

concentrations in the soil and concentrations of these elements in the vegetation were therefore related to soil pH_{H2O} only. Regressions for which the coefficients of determination were higher than 0.1 are shown in Table 11.12. Not surprisingly, none of the regression equations was significant, with F-ratios lower than 3. The results indicated that the concentration of K in stemwood and foliage was positively related to that of exchangeble K in the soil, with coefficients of determination of 0.34 and 0.20 respectively. Inclusion of the pH_{H2O} resulted in slightly higher coefficients of determination (0.39 and 0.30 respectively), with K inversely related to soil pH_{H2O}. No significant relations could be established for exchangeable Mg and Ca nor for 'available' N and P in the soil, and those in stemwood or foliage, with coefficients of determination all below 0.05.

The present method of P extraction employed a fairly weak extractant (Ca-lactate) and this undoubtedly resulted in the underestimation of 'available' P over longer periods of time. The Bray II extraction method, which was applied to the samples collected in the soil pits at the various study sites was more agressive (Dr. V.J.G. Houba, pers. comm.) and may have provided more realistic estimates in the case of trees (Sanchez, 1976). Regressions were therefore also calculated with the Bray-II P concentration in the 0-10 cm layer as independent and the average P content in foliage and stems as dependent parameters. The results showed that the P concentration in stems were positively related to Bray-II 'available' P in topsoil, whereas P in foliage showed a negative relationship to that in the soil.

Concentrations of P and Mg in stemwood were positively related to pH with coefficients of determination of 0.13 and 0.11 respectively, whereas Ca showed an inverse relationship with a coefficient of determination of 0.10 only. The concentration of Mg in foliage was positively related to pH whereas the concentrations of N, P and Ca showed an inverse relationship with soil pH.

A foliar nutrient status guide was developed for *Pinus caribaea* in Queensland by Bevege and Humphreys (1978) and this was used to determine whether any of the forest sites was likely to have nutrient deficiencies at the time of sampling (Table 11.13). The critical level for a nutrient also depends on other nutrients being adequately supplied (Mead, 1984) and deficiencies in one of the nutrients may alter the critical levels of other nutrients (Bevege, 1978). Critical levels are known to vary with forest age (Miller *et al.*, 1981) and tree provenance (Goddard and Hollis, 1984). There is also some uncertainty whether critical levels derived for a species in a specific region may be applied to the same species in other regions due to the dependency of the critical levels on environmental conditions (*e.g.* temperature, rainfall) (Mead, 1984). The foliar nutrient concentrations observed in Tulasewa, Korokula, Koromani and Oleolega forests were well above the adequacy levels as given by Bevege and Humphreys (1978), with the exception of B in Tulasewa forest (Table 11.13). This confirms the visual observation that the forests presently studied did not show any signs of nutrient stress. Boron levels in the foliage of Nabou and Ra forests (and to a lesser extent in Bua and Lololo forests) were below the suggested deficiency levels, which may cause problems similar to those observed in second rotation forests in the Lololo Estate (*e.g.* shoots without needles; Dr. J.H.R. Heuch, pers. comm.). Similarly the low N levels in the foliage collected in the Ra Estate indicate that deficiencies may occur in future rotations.

The foliar nutrient levels given in Table 11.13 show considerable variation both within and between regions, presumably reflecting differences in soil nutrient status, climate and possibly tree provenance. Furthermore, foliar nutrient levels are known to show a seasonal variation (Leaf, 1973; van den Driessche, 1974; Lamb, 1976) which may also explain part of the variation.

Foliar nutrient levels below the critical level as given by Bevege and Humphreys (1978) were observed, but this did not necessarily result in a low biomass production, as shown by the Nigerian forests which were productive (Table 11.9), in spite of very low foliar P levels. As such care should be taken when applying critical levels to predict nutrient deficiencies.

11.5.4 Forest Nutrient Content

Nutrient Content of Pines

As nutrient concentrations vary between component parts of trees (Tables 11.8 – 11.10) the pattern of nutrient accumulation will differ from that of the biomass itself. As such the largest accumulation of nutrients may be expected to occurr early in the rotation during the development of the nutrient-rich crown. After canopy closure the demand for nutrients becomes less as nutrient uptake is primarily for the production of nutrient-poor wood (Bruijnzeel, 1983a; Miller, 1984; Gholz *et al.*, 1985).

The nutrient contents of the above-ground living biomass and the within-tree distribution of nutrients for Tulasewa, Korokula and Koromani forests are given in Tables 11.14, 11.15 and 11.16 respectively. Relatively large proportions of macronutrients were observed in foliage. The foliage in Tulasewa forest accounted for 15% of the total pine biomass but the associated macronutrient content varied between 48% (P) and 59% (Ca) of the total. Due to the low concentrations in wood as compared to those in needles the nutrient content of harvestable wood, which accounted for 70% of the

Table 11.13: *Foliar nutrient status guide, average foliar nutrient concentrations and standard deviations (SD) for needles collected during the present study and in several other forest estates of Fiji Pine Ltd. on Viti Levu and Vanua Levu (Source: Fiji Pine Limited), and foliar nutrient concentrations observed in plantation forests in other tropical countries. Concentrations of macronutrients in % and those of micronutrients in ppm.*

Forest	Age	N	P	K	Ca	Mg	B	Mn	Zn	Cu
Nutrient status guide (Bevege & Humphreys, 1978)										
Adequacy		0.900	0.068	0.350	0.110	0.080	12	35	25	2
Deficiency		0.800	0.060	0.280	0.090	0.050	8	25	18	1.8
VITI LEVU										
Nabou (n=15)	Mixed	0.895	0.159	0.856	0.199	0.160	6.4	139	22	3.5
SD		0.082	0.033	0.103	0.030	0.020	1.3	36	3	0.3
Nabou, present study										
Tulasewa (n=5)	*7*	*0.995*	*0.112*	*0.594*	*0.292*	*0.185*	*8.1*	*410*	*32*	
SD		*0.132*	*0.022*	*0.122*	*0.098*	*0.026*	*2*	*158*	*14*	
Korokula (n=5)	*11*	*1.054*	*0.073*	*0.366*	*0.274*	*0.274*	*12.1*	*211*	*34*	
SD		*0.141*	*0.007*	*0.115*	*0.051*	*0.063*	*4.1*	*18*	*8*	
Koromani (n=3)	*16*	*1.064*	*0.080*	*0.657*	*0.321*	*0.160*	*12.9*	*228*	*32*	
SD		*0.009*	*0.017*	*0.298*	*0.018*	*0.018*	*3.4*	*56*	*6*	
Oleolega (n=2)	*16*	*1.137*	*0.073*	*0.683*	*0.346*	*0.164*	*17.9*	*863*	*40*	
SD		*0.171*	*0.012*	*0.110*	*0.136*	*0.056*	*2.1*	*711*	*9*	
Lololo (n=46)	Mixed	0.866	0.101	0.653	0.209	0.130	8.2	683	20	3.7
SD		0.090	0.023	0.225	0.085	0.029	1.9	674	4	0.8
Ra (n=3)	Mixed	0.738	0.146	0.593	0.252	0.192	6.7	131	21	3.2
SD		0.129	0.043	0.119	0.103	0.049	0.5	61	5	1.3
VANUA LEVU										
Bua (n=71)	Mixed	1.074	0.096	0.516	0.259	0.152	7.8	441	18	2.9
SD		0.225	0.033	0.244	0.136	0.047	7.5	307	8	0.7
BRAZIL (1)	6	2.51	0.30	0.74	0.71	0.30		50		
	5.5	1.21	0.14	0.18	0.69	0.08				
BRAZIL (2)	9.5	0.74	0.05	0.26	0.55	0.14				
SURINAM (1)	5.5	0.99	0.07	0.21	0.89	0.28				
	8.5	1.05	0.06	0.33	0.54	0.13				
	15.5	0.98	0.07	0.62	0.46	0.09				
NIGERIA (3)	6	0.94	0.04	0.72	0.33	0.17				
	10	0.87	0.03	0.75	0.35	0.18				
PUERTO RICO (4)	5	1.31	0.07	0.18						
	19.5	1.44	0.07	0.46						

(1) Chijoke, 1980; (2) Russel, 1983; (3) Egunjobi and Bada, 1979; (4) Lugo, 1992

Table 11.14: *Total nutrient content of pine trees and undergrowth, and within tree distribution of nutrients in Tulasewa forest in kg ha^{-1} dry weight in January 1990.*

Nutrient	Total (pine)	Stemwood	Stembark	Branches Dead	Branches Live	Twigs Dead	Twigs Live	Needles Dead	Needles Live	Under-growth
N	148.7	35.3	11.3	1.0	12.6	0.6	2.9		85.0	37.8
Standard deviation		*9.7*	*3.7*	*0.2*	*1.7*	*0.1*	*0.4*		*7.9*	
% of total		*23.7*	*7.6*	*0.7*	*8.5*	*0.4*	*1.9*		*57.2*	
P	18.4	5.6	1.2	0.1	1.9	0.0	0.7		8.8	3.5
Standard deviation		*0.4*	*0.4*	*0.0*	*0.3*	*0.0*	*0.2*		*1.4*	
% of total		*30.4*	*6.8*	*0.5*	*10.5*	*0.2*	*3.7*		*48.0*	
K	87.1	24.9	6.1	0.3	10.4	0.1	2.8		42.5	107.1
Standard deviation		*5.9*	*1.4*	*0.2*	*1.4*	*0.1*	*0.6*		*5.6*	
% of total		*28.6*	*7.0*	*0.4*	*11.9*	*0.1*	*3.2*		*48.8*	
Ca	80.5	17.8	3.2	1.8	8.0	0.8	1.4		47.5	18.0
Standard deviation		*1.5*	*0.6*	*0.2*	*0.9*	*0.1*	*0.2*		*8.7*	
% of total		*22.1*	*4.0*	*2.2*	*10.0*	*0.9*	*1.7*		*59.0*	
Mg	36.8	8.2	2.5	0.6	4.8	0.3	0.9		19.5	19.4
Standard deviation		*1.1*	*0.3*	*0.1*	*1.1*	*0.0*	*0.1*		*2.9*	
% of total		*22.2*	*6.8*	*1.6*	*13.0*	*0.9*	*2.5*		*53.0*	
B	0.136	0.05	0.01						0.08	0.12
Standard deviation		*0.01*	*0.00*						*0.02*	
% of total		*33.1*	*5.1*						*61.8*	
Mn	7.697	2.12	0.36						5.23	2.29
Standard deviation		*1.00*	*0.17*						*1.00*	
% of total		*27.5*	*4.6*						*67.9*	
Zn	0.786	0.41	0.07						0.31	0.03
Standard deviation		*0.26*	*0.04*						*0.08*	
% of total		*51.9*	*8.7*						*39.3*	

Table 11.15: *Total nutrient content of pine trees and undergrowth, and within tree distribution of nutrients in Korokula forest in kg ha^{-1} dry weight in January 1990.*

Nutrient	Total	Stemwood	Stembark	Branches Dead	Branches Live	Twigs Dead	Twigs Live	Needles Dead	Needles Live	Undergrowth
N	205.7	51.2	17.0	1.9	16.8	0.6	5.3		112.9	7.3
Standard deviation		*12.8*	*3.1*	*0.2*	*3.3*	*0.1*	*2.1*		*11.3*	
% of total		*24.9*	*8.3*	*0.9*	*8.2*	*0.3*	*2.6*		*54.9*	
P	30.4	11.4	7.5	0.4	2.3	0.1	0.8		8.0	0.7
Standard deviation		*6.4*	*6.2*	*0.4*	*0.6*	*0.1*	*0.4*		*0.6*	
% of total		*37.4*	*24.8*	*1.2*	*7.5*	*0.2*	*2.8*		*26.2*	
K	85.9	27.7	5.6	0.5	9.2	0.1	3.3		39.5	20.6
Standard deviation		*5.0*	*1.5*	*0.1*	*1.5*	*0.0*	*1.0*		*8.5*	
% of total		*32.3*	*6.5*	*0.6*	*10.7*	*0.1*	*3.9*		*46.0*	
Ca	114.0	37.0	8.0	3.1	14.3	0.9	2.4		48.4	3.5
Standard deviation		*5.0*	*3.7*	*0.8*	*3.6*	*0.2*	*0.8*		*23.2*	
% of total		*32.4*	*7.0*	*2.7*	*12.5*	*0.7*	*2.1*		*42.5*	
Mg	66.8	17.1	5.1	1.0	7.4	0.3	1.8		34.0	3.7
Standard deviation		*1.4*	*1.2*	*0.2*	*1.2*	*0.1*	*1.0*		*8.0*	
% of total		*25.5*	*7.7*	*1.6*	*11.1*	*0.5*	*2.8*		*51.0*	
B	0.241	0.09	0.01						0.14	0.02
Standard deviation		*0.02*	*0.00*						*0.03*	
% of total		*35.3*	*5.4*						*59.3*	
Mn	8.172	4.06	0.62						3.49	0.44
Standard deviation		*1.92*	*0.30*						*0.60*	
% of total		*49.6*	*7.6*						*42.7*	
Zn	1.243	0.78	0.12						0.34	0.01
Standard deviation		*0.50*	*0.08*						*0.09*	
% of total		*63.0*	*9.7*						*27.3*	

total biomass, was low ranging from 26% (Ca) to 37% (P) of the total. In Korokula forest the foliage, accounting for 11% of the total biomass, contained between 26% (P) and 55% (N) of the total nutrient content, whereas the harvestable wood (75% of the total biomass) contained between 25% (N) to 37% (P) of the total. Similar values were obtained for Koromani forest where the macronutrient content of the foliage (7% of biomass) varied between 33% (P) and 47% (N) of the total and harvestable wood (80% of biomass) contained 42% (N) to 54% (P) of the total. Similar patterns have been reported for a range of tropical forest plantations, both hardwood (George, 1977; Bruijnzeel, 1983a; Hase and Fölster, 1982) and coniferous ones (Lundgren, 1978; Chijioke, 1980; Bruijnzeel, 1984).

The micronutrients Mn and B showed patterns that were similar to those of the macronutrients. However, harvestable wood contained a larger proportion of the total Zn content (61%, 63% and 79% in the Tulasewa, Korokula and Koromani forest plots respectively) as a result of the relatively high concentration in the stem (11±7 ppm; Table 15.2).

The total nutrient contents of the Tulasewa, Korokula and Koromani stands in January, 1990, and in September, 1991, as well as that predicted for January 1991 (sound and damaged forest) are given in Table 11.17. Mean annual and current rates of uptake plus predicted returns of nutrients to the forest floor by cyclone Sina are shown as well. Not surprisingly, the current annual nutrient uptake was highest in

Table 11.16: *Total nutrient content and within-tree distribution of nutrients in kg ha^{-1} dry weight in Koromani forest (January 1990).*

Nutrient	Total	Stemwood	Stembark	Branche		Twigs		Needles		Under-growth
				Dead	Live	Dead	Live	Dead	Live	
N	235.4	74.2	23.9	3.0	19.4	0.5	4.5		110.1	15.4
Standard deviation		*15.2*	*5.3*	*0.7*	*2.3*	*0.0*	*0.4*		*11.2*	
% of total		*31.5*	*10.2*	*1.3*	*8.2*	*0.2*	*1.9*		*46.8*	
P	22.5	10.2	2.0	0.2	2.2	0.0	0.6		7.4	1.4
Standard deviation		*3.1*	*0.8*	*0.1*	*0.6*	*0.0*	*0.1*		*1.1*	
% of total		*45.1*	*8.7*	*1.0*	*9.6*	*0.1*	*2.6*		*32.8*	
K	132.5	49.8	12.3	1.1	14.1	0.1	3.6		51.6	43.8
Standard deviation		*7.1*	*5.6*	*0.1*	*3.0*	*0.1*	*0.8*		*12.3*	
% of total		*37.6*	*9.3*	*0.8*	*10.6*	*0.1*	*2.7*		*38.9*	
Ca	165.3	62.0	15.9	4.6	22.3	0.9	3.3		56.4	7.3
Standard deviation		*10.2*	*7.4*	*1.2*	*4.4*	*0.2*	*0.9*		*12.4*	
% of total		*37.5*	*9.6*	*2.8*	*13.5*	*0.5*	*2.0*		*34.1*	
Mg	53.0	20.3	5.3	0.9	6.7	0.2	1.3		18.3	7.9
Standard deviation		*3.0*	*1.8*	*0.1*	*0.7*	*0.0*	*0.3*		*4.3*	
% of total		*38.4*	*10.0*	*1.8*	*12.6*	*0.3*	*2.4*		*34.5*	
B	0.295	0.12	0.02						0.16	0.02
Standard deviation		*0.03*	*0.00*						*0.03*	
% of total		*41.3*	*5.7*						*52.9*	
Mn	14.421	5.79	0.80						7.83	0.93
Standard deviation		*2.74*	*0.38*						*6.43*	
% of total		*40.1*	*5.5*						*54.3*	
Zn	1.609	1.12	0.15						0.34	0.05
Standard deviation		*0.71*	*0.10*						*0.07*	
% of total		*69.4*	*9.6*						*21.0*	

Table 11.17: *Total nutrient content of above-ground living tree biomass in Tulasewa, Korokula and Koromani forests at various stages during the study plus estimated annual rates of uptake as well as amounts of nutrients released by cyclone Sina. Micronutrients in the stem (wood+bark) were calculated from concentrations obtained for trees in the Oleolega drainage basin. Amounts in kg ha^{-1} dry weight.*

						In stem and foliage			In foliage		
	N	P	K	Ca	Mg	B	Mn	Zn	B	Mn	Zn
TULASEWA FOREST, Planted 1984											
Jan '90	148.66	18.35	87.14	80.49	36.75	0.136	7.70	0.79	0.084	5.23	0.31
Sep '91	99.53	13.04	61.56	53.03	25.07	0.090	4.88	0.61	0.040	2.49	0.15
Jan '91, predicted											
Sound forest	183.72	23.10	109.50	98.87	45.58	0.169	9.40	1.03	0.095	5.88	0.35
Cyclone damaged	92.48	12.07	57.01	49.35	23.30	0.084	4.54	0.56	0.038	2.38	0.14
Actual uptake	-49.13	-5.31	-25.58	-27.46	-11.68	-0.046	-2.82	-0.18	-0.044	-2.74	-0.16
Mean annual uptake	24.78	3.06	14.52	13.42	6.13	0.023	1.28	0.13	0.014	0.87	0.05
Uptake in 1990	35.06	4.75	22.36	18.38	8.83	0.033	1.70	0.24	0.011	0.65	0.04
Cyclone release	91.24	11.03	52.49	49.52	22.28	0.085	4.86	0.47	0.057	3.50	0.21
KOROKULA FOREST, Planted 1979											
Jan '90	206.00	30.44	86.05	114.16	66.91	0.241	8.17	1.24	0.143	3.49	0.34
Sep '91	167.89	27.35	72.34	97.15	55.29	0.194	6.96	1.12	0.098	2.39	0.23
Jan '91, predicted											
Sound forest	215.22	32.22	90.27	119.94	70.01	0.253	8.62	1.32	0.146	3.57	0.35
Cyclone damaged	165.19	26.81	71.10	95.44	54.38	0.191	6.83	1.09	0.097	2.37	0.23
Actual uptake	-38.10	-3.09	-13.70	-17.01	-11.63	-0.047	-1.21	-0.13	-0.045	-1.10	-0.11
Mean annual uptake	18.73	2.77	7.82	10.38	6.08	0.022	0.74	0.11	0.013	0.32	0.03
Uptake in 1990	9.22	1.79	4.22	5.78	3.09	0.012	0.45	0.08	0.003	0.08	0.01
Cyclone release	50.04	5.41	19.17	24.50	15.62	0.062	1.79	0.23	0.049	1.21	0.12
KOROMANI FOREST, Planted 1975											
Jan '90	235.42	22.54	132.52	165.29	52.96	0.295	14.42	1.61	0.156	7.83	0.34
Sep '91	211.83	20.98	121.53	153.35	49.08	0.261	12.74	1.54	0.122	6.13	0.26
Jan '91, Predicted											
Sound forest	246.26	23.73	139.08	173.76	55.67	0.309	15.07	1.71	0.160	8.01	0.35
Cyclone damaged	213.17	21.11	122.30	154.33	49.40	0.263	12.82	1.55	0.123	6.16	0.27
Actual uptake	-23.59	-1.56	-10.99	-11.94	-3.88	-0.034	-1.68	-0.07	-0.034	-1.70	-0.08
Mean annual uptake	15.69	1.50	8.83	11.02	3.53	0.020	0.96	0.11	0.010	0.52	0.02
Uptake in 1990	10.84	1.19	6.56	8.47	2.71	0.014	0.65	0.10	0.004	0.18	0.01
Cyclone release	33.09	2.62	16.78	19.43	6.27	0.045	2.25	0.16	0.037	1.85	0.08

Tulasewa forest and exceeded the mean annual uptake. The converse was true for the other sites, which indicates that nutrient requirements are largest between age 6 and 10. This is consistent with the high CAI for nutrient-rich foliage biomass observed for Tulasewa (Table 11.7).

On the basis of predictions suggested by Table 11.17 cyclone Sina released 50%, 21% and 12% of the nutrients stored in the above-ground living biomass of Tulasewa, Korokula and Koromani forests respectively. This resulted in reductions of respectively 31%, 15% and 8% in the nutrient content of the above-ground pine biomass in September, 1991, as compared to those in January, 1990. Even larger reductions were observed in the Luquillo Experimental Forest in Puerto Rico, where hurricane Hugo in 1989 reduced the above-ground biomass of natural rain forest by 50%, with associated decreases in the nutrient content of 45% (N), 46% (P) and 48% (K, Ca, Mg) of pre-hurricane values (Scatena *et al.*, 1993).

Nutrient Content of Undergrowth

No direct estimates were made of the amounts of nutrients stored in the undergrowth of the respective study sites as the uptake of nutrients during the growing season is likely to be balanced by their release during the dry season (*cf.* Section 10.3). In Tulasewa forest the pre-cyclone undergrowth was dominated by *Pennisetum polystachyon* and its nutrient content was therefore assumed to be similar to the values given in Table 10.4. On this basis the pre-cyclone nutrient content of the undergrowth at Tulasewa will have amounted to 16–30% of that of the pines for N, P, Ca, B, Mn and Zn, about 54% of that of the pines for Mg, whereas the K content of the undergrowth may have exceeded that of the pines by a factor of 1.26 (Table 11.14). The large reduction in the undergrowth biomass between age 6 and 11 will therefore result in the release of significant amounts of nutrients (particularly K) potentially for uptake by the pine trees. The undergrowth grew vigorously after the reduction in stand density caused by cyclone Sina and the proportion of nutrients in the undergrowth will therefore have been considerably higher than the values presented above.

Rough estimates of the pre-cyclone nutrient contents of the undergrowth in Korokula and Koromani forests were obtained by multiplying the concentrations of nutrients in mission grass times the estimated undergrowth biomass in these forests (Section 11.5.1) and these are presented in Tables 11.15 and 11.16, respectively. As the composition of the undergrowth vegetation in Korokula and Koromani forests was different from that of grassland, a substantial error may have been introduced in this way. However, because the estimated amounts of nutrients in the undergrowth were low compared to those in the pines (<6% for N, P, and Ca, 6–15% for Mg and 24–33% for K) the associated error in the overall nutrient budget was considered small. In the Korokula and Koromani stands large changes were not observed between the pre- and post-cyclone undergrowth, and the proportion of nutrients in the undergrowth may have been only slightly higher than the values presented above in September 1991.

11.6 Forest Development and Nutrient Accumulation

Plantation Development

Naturally, the development of pine plantations in Fiji is strongly affected by the frequency of cyclone occurrence during a rotation. Cyclone damage had considerably reduced the stocking of the study forests compared to that at planting. In November 1990 cyclone Sina effectively wrecked Tulasewa forest and to a lesser extent the Ole-olega forest, whereas Korokula and Koromani forests were defoliated. This created additional gaps and caused an increase in the variation of the LAI (*cf.* Sections 6.4.1 and 11.3.6). Pre-cyclone diameter increments were high, but decreased after cyclone Sina, presumably as a result of the need to regenerate foliage that had been blown away by the cyclone (Section 11.4). Tree heights also varied widely in the forests as a result of previous cyclone damage to the crowns (*e.g.* stem snap). Crown interlock occurred between age 6 and 10, at a stocking of 820–830 trees ha^{-1}.

Pinus caribaea plantation forests have been established succesfully in countries with distinctly different climates (*i.e.* in terms of rainfall amounts and distribution) and soils (Evans, 1992). Some backgound information on these forests is provided in Table 11.18 for comparison with the forests presently under consideration. Due to the large variation in stocking between the various plantations it is difficult to generalize on the effects of climate or geology on diameter and height increments. Comparison with forests of comparable stocking and age revealed that tree growth in Tulasewa forest was much better than that of the Nigerian forest at Kaduna (Kadeba, 1991), possibly as a result of the lesser amounts of rainfall and of site fertility. Similarly, the growth of Koromani forest was comparable to that of a mature pine forest in Puerto Rico, another area with volcanically derived soils and occasional cyclones (Lugo, 1992).

Biomass Accumulation

Comparison between the grassland and forest sites showed that the total living biomass increased from an initial maximum of 8000 kg ha^{-1} for grassland during the wet season (Section 10.3) to about 150 t ha^{-1} for a mature plantation forest (*e.g.* Koromani forest, Section 11.5.1). Carden (1979) reported a biomass of 185 t ha^{-1} for a 'typical' 15-year-old plantation forest in Fiji with a stocking of 832 trees ha^{-1}. This compares well with the present study, considering the difference in stocking between Koromani forest (620 trees ha^{-1}) and that of Carden (1979). Figure 11.7 shows the changes in tree biomass, mass of utilizable wood, foliage and undergrowth over a rotation period as obtained from the biomass data collected during the present study.

The observed increase in pine biomass was largest during the first 10 years after plantation establishment. However, the lower productivity of the older forest could be fully explained by the loss of production as a result of cyclone damage, which reduced the stocking by 26% in Koromani forest compared to that of Tulasewa forest (pre-cyclone situation). As shown in Figure 11.7 the mass of utilizable wood increased at a fairly uniform rate throughout the rotation period, whereas crown development slowed down between age 6–11. The accumulation of above-ground pine plus undergrowth biomass (M_f, in kg ha^{-1}) with increasing forest age (A_f, in years) could be described by the regression equation:

$$M_f = 9227(\pm 335) \cdot A_f + 10633(\pm 3759)$$

Table 11.18: *Site and forest characteristics of Pinus caribaea var. hondurensis plantation forests in various tropical countries.*

Location	Rock type	Height [m]	Rainfall [mm]	Dry months	Age [years]	Stocking [trees/ha]	Dbh [cm]	H [m]	Reference
FIJI									
Tulasewa	AV	116	1800	6	6	826	15.6	11.6	Present study
Korokula	AV	50			11	822	20.4	14.7	
Koromani	AV	90			15	621	24.9	17.5	
BRAZIL									
Jari Florestal	S	50	2300	5	6	981			Chijioke (1980)
Jari Florestal	S	50	2300	5	9.5	1033	23.6	18.2	Russel (1983)
NIGERIA									
Kaduna	IM	610	1250	5	5	842	10.5	8.8	Kadeba (1991)
					7	1036	14.4	9.6	
					9	1100	15.8	11.6	
					11	999	17.9	13.8	
					15	1201	20.1	17.4	
Ibadan	IM	230	1330	5	6	2634	12.2	10.3	Egunjobi (1975)
					8	2390	10.5		
					9	2767	12.6		
					10	2866	14		
AUSTRALIA									
Beerburrum	S	20	1100	5	5	1153			Richards and Bevege (1967)
PUERTO RICO									
Luquillo	AV	350	3360	0	11	1400	17.5		Cuevas et al. (1991)
Luquillo	AV	220	3900	0	4	1290	14	8	Lugo (1992)
		580			18.5	850	27.8	18	

AV: Acid volcanic; S: Sedimentary; IM: Igneous/metamorph

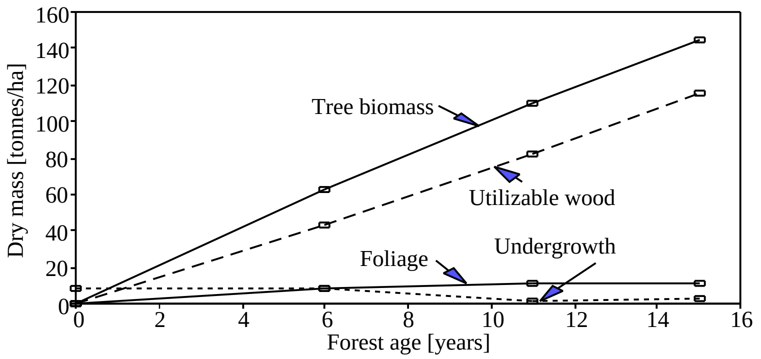


Figure 11.7: *Changes in tree biomass, mass of utilizable wood, foliage biomass and undergrowth biomass over a rotation period.*

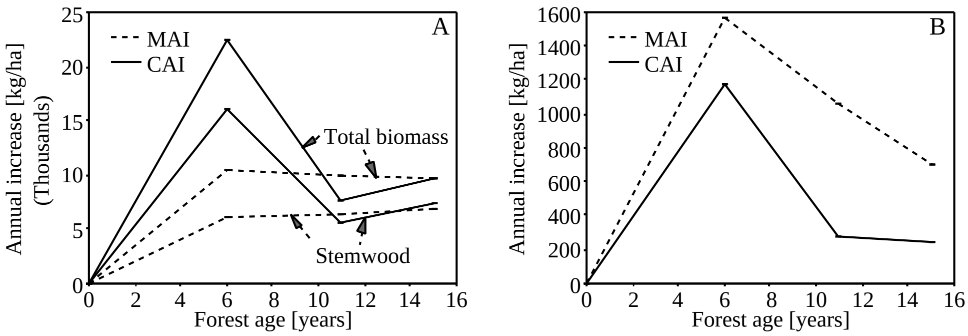


Figure 11.8: *Changes in CAI and MAI (kg ha^{-1}) over a rotation for (A) total stemwood, biomass and (B) foliage.*

$$\text{n}=4,\ r^2 = 1.00 \tag{11.3}$$

Similarly, the following expression was obtained for the accumulation of above-ground pine biomass with stand age:

$$M_f = 9813(\pm 128) \cdot A_f$$
$$\text{n}=4,\ r^2 = 1.00 \tag{11.4}$$

where the regression constant b was forced to zero to avoid a finite pine biomass at zero forest age.

At the current spacings of 2*3 m or 3*3 m crown interlock occurred shortly after age 6 when the foliage biomass production levelled off. This coincided with a change in undergrowth biomass, which decreased from about 8000 kg ha^{-1} to 1500–3000 kg ha^{-1} at the end of the wet season, as well as with a change in the undergrowth composition. The proportion of mission grass decreased from 93% of the total in grassland to 37% in the 15-year-old forest, where bushes and young native trees reappeared. The decrease in undergrowth biomass may is likely to be the result of reduced light conditions below the closed canopy (Section 11.3.6), whereas the change in composition could be attributed to the protection of the forests from fire, which allowed the survival of seedlings which would normally die during regular burns.

The changes in the MAI and CAI of total biomass and stemwood with forest age are shown in Figure 11.8A, whereas those for foliage are shown separately in Figure 11.8B. The MAI of total biomass decreased slightly after age 6, which may partly be due to the decrease in stocking in the older stands (*e.g.* Koromani forest) related to cyclone damage. However, the MAI of stemwood increased from 6188 kg ha^{-1} in Tulasewa forest to 6772 kg ha^{-1} in Koromani forest, with a corresponding decrease in the MAI for needles from 1500 kg ha^{-1} to 700 kg ha^{-1}. As such there is a shift towards wood production once the crown has been fully developed. The CAI for total biomass in Tulasewa forest was some 200% higher than the MAI, indicating that the forest at age six was producing biomass at a much higher rate than during the previous years. The CAI was similar to the MAI for the older forests suggesting that biomass production had peaked at age 6 or shortly thereafter. The current productivity of Korokula forest (age 11) was lower than that during previous years as the CAI was lower than the MAI, which may be related to the relatively poor quality of the soil at this site (Chapter 4).

Table 11.19: *Total and stem biomass and mean annual increments for Pinus caribaea plantations in Fiji and other tropical countries.*

Location	Elevation [m]	Age [years]	Biomass (tonnes/ha) Tree	Stem	Foliage	MAI (tonnes/ha) Tree	Stem	Reference
FIJI								
Tulasewa	116	6	62.2	43.3	9.4	10.4	7.2	Present study
Korokula	50	11	109.4	82.1	11.7	9.9	7.5	
Koromani	90	15	144.8	115.6	10.6	9.7	7.1	
BRAZIL								
Jari Florestal	50	6	66.0	53.7	7.2	11.0	9.0	Chijioke (1980)
Jari Florestal	50	9.5	212.1	161.0	28.1	22.3	16.9	Russell (1983)
NIGERIA								
Kaduna	610	5	18.1	12.1	3.4	3.6	2.4	Kadeba (1991)
		7	50.6	36.3	8.1	7.2	5.2	
		9	78.0	56.2	12.0	8.7	6.2	
		11	105.2	78.5	14.4	9.6	7.1	
		15	161.2	126.9	18.3	10.7	8.5	
Ibadan	230	6	68.3	47.4	11.5	11.4	7.9	Egunjobi (1975)
Ibadan	230	6	62.0	43.9	9.8	12.9	7.3	Egunjobi and Bada (1979)
		8	57.7	42.2	9.1	9.0	5.3	
		9	108.0	80.0	15.7	14.8	8.9	
		10	144.4	97.4	20.2	17.9	9.7	
AUSTRALIA								
Beerburrum	20	5	58.7			11.7		Richards and Bevege (1967)
PUERTO RICO								
Luquillo	350	11	94.9			9.5		Cuevas et al. (1991)
Luquillo	220	4	38	27*	11	9.5		Lugo (1992)
	580	18.5	166	131*	35	9.0		

*: Branches included

A comparison of the total biomass, stemwood biomass and MAI for the forests in Fiji and those of plantation forests in various other tropical countries is presented in Table 11.19. Data on annual rainfall, stocking, tree diameter and height for the respective forests have already been presented in Table 11.18. The relationship of stem biomass *versus* forest age is given in Figure 11.9. The biomass production of the forests in Fiji was comparable to those of the forests elsewhere, in spite of the relatively low stocking. The large variation in annual rainfall amounts and soils between sites therefore seems to have little effect on biomass production. For instance, the production of the dry Nigerian forests was similar to those of forests in the more humid areas of Fiji, Brazil and Puerto Rico. The biomass of a 9.5-year-old *Pinus caribaea* plantation in Jari Florestal, Brazil, (Russell, 1983) was exceptionally high when compared to that of a 6-year-old plantation of similar stocking in the same area (Chijioke, 1980). However, Russell (1983) obtained his value for a very small plot (0.03 ha, 31 trees), which may have affected the result as the spatial variation in biomass may not have been covered adequately.

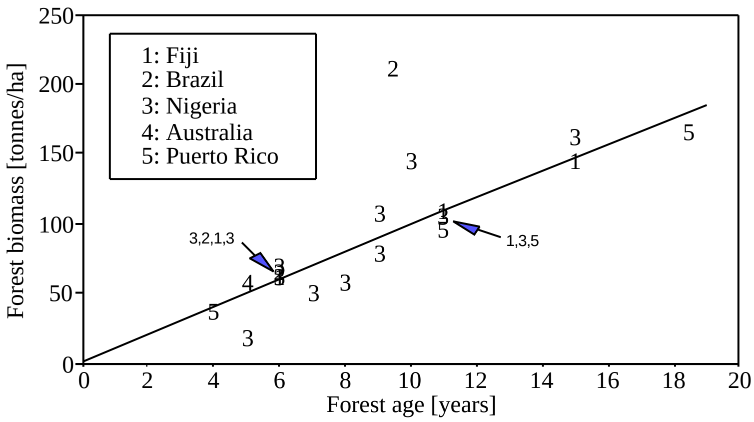


Figure 11.9: *Above-ground biomass* versus *forest age for Pinus caribaea plantation forests in various tropical countries. The solid line describes the accumulation of biomass with forest age for the Fiji plantations.*

Nutrient Accumulation in Biomass

As indicated earlier, the false time series approach may describe accumulation of the biomass and biomass nutrient content during a rotation period accurately, provided that the pre-planting soil conditions, and other environmental circumstances at the various forests are similar (Hase and Fölster, 1982; Bruijnzeel, 1983a). Although the soils in the grassland and forest plots were typical for those in the Nabou Forest Estate area, significant differences were observed in their nutrient status and physical characteristics (Chapter 4). This will almost certainly have affected the forest nutrient content (*cf.* Section 11.5.3), and possibly also the biomass accumulation, rendering the false time series approach more or less invalid. The approach was further complicated by the large spatial variation in stocking, and therefore biomass, within older stands due to differences in damage by cyclones. However, this may be viewed as typical for the Fijian situation and a reduction in biomass over the period of a rotation due to cyclone damage cannot be avoided.

The accumulation of macronutrients with increasing forest age is shown in Figure 11.10. As indicated earlier, the nutrient uptake of Tulasewa forest in 1990 was higher than the mean annual uptake, whereas the converse was true for the older forests. As such the maximum annual nutrient uptake occurs somewhere between age 6 and 11, coinciding with the development of the crown. Large fluctuations were observed for the accumulation of K. These are most likely to be caused by differences of exchangeable K in the soils (Chapter 4), which was shown to affect concentrations of this nutrient in stemwood as well as in foliage (Section 11.5.3). Although this illustrated the limitations of the false time series in predicting the accumulation of K, better results were obtained for the other macronutrients which were less influenced by differences in the site quality (Figure 11.10). Taking the respective figures at face value Tulasewa forest contained 2.6 (Mg) to 4.4 (P) times the amount of nutrients in grassland vegetation and litter at the end of the wet season (Table 10.4). After the canopy had been fully developed nutrient uptake decreased somewhat and Koromani forest contained 3.0 (Mg) to 6.0 (Ca) times the amounts present in grassland biomass

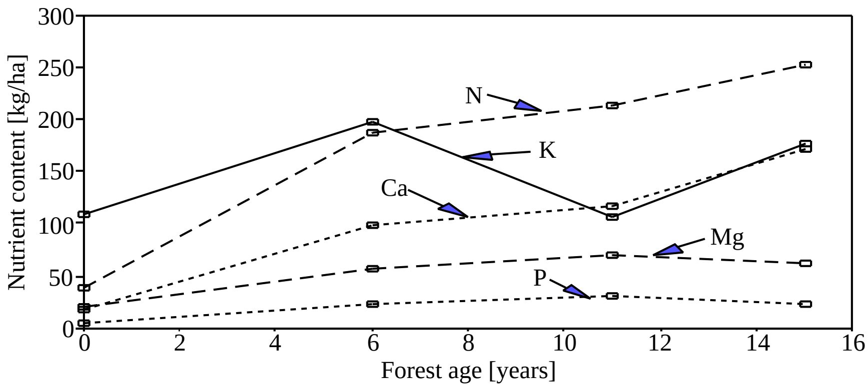


Figure 11.10: *Accumulation of N, P, K, Ca and Mg in pine trees and undergrowth during a rotation period.*

Table 11.20: *Linear regression constants, standard errors (between brackets) and coefficients of determination for expressions describing the changes in nutrient content (kg ha^{-1}) of the above-ground forest biomass (including undergrowth) with increasing forest age (years). Lines were fitted through four data points representing age 0, 6, 11 and 15 years.*

Nutrient	a	b	r2	Nutrient	a	b	r2
N	2.47(0.07)	34.62 (0.76)	1.00	**Mg**	1.42 (0.57)	10.20 (6.42)	0.75
P	0.05 (0.01)	2.17 (0.11)	0.94	**Mn**	0.21 (0.09)	1.65 (0.98)	0.75
K	0.34 (0.25)	5.97 (2.82)	0.48	**B**	0.0048 (0.0026)	0.0284 (0.0296)	0.62
Ca	4.35 (0.64)	23.22 (7.22)	0.96	**Zn**	0.0004 (0.0022)	0.1180 (0.0252)	0.01

at the end of the wet season, although these values may have been influenced by the rather low soil nutrient status of the Koromani site. Similar accumulation patterns were observed for Mn, B and Zn of which the amounts at the end of the rotation were 4.4, 5.8 and 6.9 times those observed in grassland respectively (*cf.* Tables 10.4 and 11.17).

Linear regression equations ($Y = a \cdot X + b$) were calculated to describe nutrient accumulation in pine biomass (Y) as a function of forest age (X). The resulting regression constants and the coefficients of determination are given in Table 11.20. The regression coeffient a represents the mean annual increase in the content of the nutrient under consideration. Not surprisingly, a low coefficient of determination was found for K due to the low value of this nutrient in Korokula forest (Table 11.10).

A large part of the variation caused by differences in site quality disappears when the nutrient content of a tree component (including K) is expressed as a fraction of total forest nutrient content (including undergrowth and litter standing crop). This is shown in Figure 11.11 where the accumulations of macronutrients and Zn in merchantable wood are expressed as a fraction of the total. Zn had not been analysed in branches and twigs and the total therefore consisted of Zn in stems, foliage, undergrowth and needle

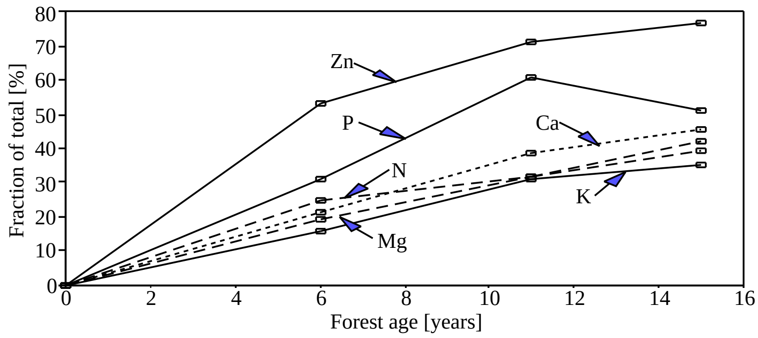


Figure 11.11: *Accumulation of macronutrients and Zn in merchantable wood over the period of a rotation expressed as a fraction of the total in trees, undergrowth and litter.*

litter. The values presented for Zn in Figure 11.11 are therefore slightly overestimated. The figure shows that 35–45% of the total N, K, Ca and Mg contents of the vegetation is removed at the end of a rotation when tree stems are harvested. These percentages are much higher for P (up to 60%) and Zn (up to 77%). Because 'available' P is fairly low in the soils under study (Chapter 4) deficiencies of P, and possibly Zn, may occur in future rotations. Fractions of Mn and B removed in merchantable timber wood are not shown but were similar to those of N, K, Ca and Mg. Since amounts of available micronutrients in the soil were not determined the potential for depletion of these nutrients by harvesting could not be evaluated, and further research is necessary on this subject.

The nutrient contents of *Pinus caribaea* plantation forests in Brazil, Nigeria and Puerto Rico are shown in Table 11.21 together with the results of the present study. The nutrient contents for forests of similar age varied considerably. Very high values for all nutrients were obtained by Russell (1983), which may partly be due to the exceptionally high biomass derived for this site (Table 11.19). The values published for Puerto Rico (Lugo, 1992) included nutrients in pines as well as in other overstory species growing in the plantation, which may explain the high nitrogen contents. The Fiji forests seem to contain somewhat lower amounts of N than most other plantations elsewhere but occupy intermediate positions with respect to some other macronutrients.

Table 11.21: *Nutrient contents of Pinus caribaea plantation forests at various locations in the tropics. All amounts are in kg ha^{-1} dry weight.*

Location	Elevation [m]	Age [years]	Forest Nutrient Content [kg/ha] N	P	K	Ca	Mg	Reference
FIJI								
Tulasewa	116	6	149	18	87	81	37	Present study
Korokula	50	11	206	30	86	114	67	
Koromani	90	15	235	23	133	165	53	
BRAZIL								
Jari Florestal	50	6	197	33	46	78	25	Chijioke (1980)
Jari Florestal+	50	9.5	673	51	218	392	136	Russell (1983)
NIGERIA								
Ibadan	230	6	221	10	126	98	40	Egunjobi and Bada (1979)
		10	374	18	258	187	74	
PUERTO RICO								
Luquillo*	220	4	342	12	36			Lugo (1992)
	580	18.5	1359	22	441			

*: includes nutrients in pines as well as in other overstory trees

Chapter 12

Litter Dynamics and Associated Nutrient Fluxes

12.1 Introduction

This chapter deals with the amounts of nutrients returned to the forest floor in litterfall, the rate of litter decomposition, and the accumulation of organic matter and nutrients on the forest floor. The object of the study was to provide an answer to the question to what extent immobilization of nutrients occurs in the litter layer, as frequently observed under pines in temperate (Will, 1967; Ballard and Will, 1981; Carey *et al.*, 1982; Gholz *et al.*, 1985) and tropical climates (Egunjobi and Bada, 1979; Chijioke, 1980; Cuevas *et al.*, 1991; Lugo, 1992; Gunadi, 1993b).

Nutrients returned to the forest floor in litterfall and subsequently released by decomposition constitute an important component of the internal nutrient cycle of a forest ecosystem. Litterfall is generally low during the first few years after establishment of a plantation (canopy development phase) and consists mainly of foliage, whereas later on in the rotation woody litterfall (*e.g.* branches, cones) becomes increasingly more important (Gholz *et al.*, 1985). Amounts of litter production generally depend on species (deciduous, coniferous), climate (*e.g.* rainfall, wind speed), soil (water holding capacity, nutrient status) and forest characteristics (*e.g.* stocking, age) (Bray and Gorham, 1964).

Few studies have been made of litterfall in *Pinus caribaea* plantation forests. The only data available are those of plantations in Nigeria (Egunjobi and Fasehun, 1972; Egunjobi, 1975; Kadeba and Aduayi, 1985; Kadeba, 1991) and in Puerto Rico (Cuevas *et al.* 1991; Lugo, 1992), which grow under rather different rainfall regimes than in Fiji. A comparison with amounts of litter production and nutrient returns at these sites will be made at the end of Section 12.6.

If the rate of decomposition is lower than that of litter production, accumulation of organic matter on the soil surface will occur, with associated immobilization of nutrients which in turn can lead to nutrient deficiencies on poor soils and reduced growth of the vegetation (Lutz and Chandler, 1946). The rate of decomposition depends on the interaction of biological (presence of soil fauna, fungi and bacteria), physical (temperature, litter layer moisture content) and chemical (soil nutrient status and litter quality) factors (Swift *et al.*, 1979). Although it is often claimed that decomposition proceeds at faster rates in the tropics (*cf.* Jordan, 1989), others (*e.g.* Anderson *et al.*, 1983; Anderson and Swift, 1983) have suggested otherwise.

The rate and patterns of release of the various nutrients from coniferous litter vary considerably in the temperate zone, where most of the research on litter decomposition has been conducted. Potassium and phosphorus seem to be very mobile with sharp drops in concentrations shortly after incubation and relatively stable levels afterwards (Burgess, 1956; Will, 1967). However, the rapid initial release of these nutrients is caused by leaching rather than by decomposition as this process has hardly begun within the first three months (Will, 1967). Nitrogen levels on the other hand generally increase until the N concentration is high enough (critical N concentration) to satisfy the requirements of the decomposer population (Berg and Staaf, 1981) after which N levels remain stable. Therefore N is immobilized until the critical concentration is reached and then released at the rate of weight loss (Gosz, 1984). Because carbon levels remain fairly stable during decomposition the C/N ratio decreases from a high initial level to a stable lower level at which N and C are released at similar rates. Ca and Mg are generally released more slowly (Burgess, 1956; Will, 1967) and often accumulate in the litter layer during the growth of a forest.

The ratio (K_L) of annual litter production to amount of litter on the forest floor is often used as an indication of the turnover rate of litter under steady state (*i.e.* non-seasonal) conditions (Swift *et al.*, 1979). Kimmins (1987) reported an annual K_L-value of 0.28 for temperate evergreen coniferous forests. However, differences in decomposition rates (read: K_L) among locations or forest types are often difficult to interprete, partly because turnover rates only represent net dissapearance rates from the litter layer and do not explicitly refer to the processes involved, such as mineralization of elements, their uptake by roots within the litter layer, or their translocation of into the soil (Burghouts, 1993). This is illustrated by a comparison of K_L values obtained for *Pinus caribaea* plantations growing under rather different climatic conditions. Egunjobi and Onweluzo (1979) and Kadeba and Aduayi (1985) reported very low annual K_L-values (0.28–0.31) for *Pinus caribaea* litter in 7–10 year old plantation forests in the dry zone of Nigeria (annual rainfall 1330 mm), where the wet season constituted the most active period of decomposition. The low turnover rate resulted in an increase of the amount of litter on the forest floor from 3700 kg ha^{-1} at age 6 to 19710 kg ha^{-1} at age 10 (Egunjobi and Bada, 1979). In contrast, Cuevas *et al.* (1991) and Lugo (1992) found high annual K_L-values (0.9–1.5) in 11–20 year old *Pinus caribaea* plantations on a mountain slope in Puerto Rico (annual rainfall: 3800 mm) where amounts of litter on the forest floor reached values of 10.5–18.9 t ha^{-1}. The range of K_L may therefore be large (0.3–1.5) for a single species and local factors (*e.g.* climate, soil) seem very important in the decomposition process.

On the other hand various investigators working in stands of *Pinus merkusii* planted on volcanic soils in Central Java, Indonesia, have reported reasonably similar values for K_L (0.66; Bruijnzeel, 1983a; Sutjahjo, 1975) Gunadi (1993a) reported low needle litter turnover rates in the very wet season (K_L= 0.2) and higher rates during the dry season (K_L= 0.8) with and annual value of 0.50 for a rather open 32 year old *Pinus merkusii* plantation (annual rainfall 3450 mm) on sandier soils in the same area. Lundgren (1978) reported the very low value of 0.2 for a 20-year-old plantation of *Pinus patula* growing on volcanic soils in upland Tanzania where the low raionfall (1060 mm year^{-1}) may have been limiting decomposition.

Amounts and nutrient contents of litter on the forest floor at the study sites will be discussed in Section 12.5.

12.2 Methods and Instrumentation

Monthly amounts of litterfall in the study sites were determined in each plot using 8 litter traps (0.25 m^2) from December 1989 (Tulasewa) and February 1990 (Koromani) until June 1990, and 12 from July 1990 until October, 1991. The traps were emptied once a month during the dry season and twice a month during the wet season to avoid losses of nutrients (Proctor, 1983) by decomposition and leaching (particularly K). The litter was dried and the weights of pine needles, woody parts (stemwood, bark, twigs and branches), male flowers, cones, seeds and undergrowth were determined separately. For each study site, bulked monthly needle litter samples were sent to FRI, New Zealand, for chemical analysis. The nutrient concentrations in woody litter, male flowers and undergrowth litter were obtained from single bulk samples of each component prepared at the end of the study for each site.

Litter decomposition rates were measured using the meshbag technique (Will, 1967). All litter bags were made from chemically inert wire mesh (1 mm mesh) and measured 15*20 cm. Openings on the sides, where the top and bottom of the bags were stitched together, permitted entry to soil fauna whereas the loss of needles through these openings was avoided. Each bag contained a dead twig and 15 grammes of air-dry green–yellow needles stripped from the lower branches of several trees in each of the stands. Initial subsamples of the air dry twigs and needles were dried at 70 °C to obtain conversion factors from air-dry to oven-dry weights. In each forest 25–30 litter bags were placed on the litter layer and covered with a thin layer of fresh needle litter to avoid detection and theft. The rate of decomposition was estimated by regularly (at three-month intervals) removing increasing numbers of bags (3–7) at a time in each forest plot and recording the air-dry and oven-dry weights of their contents (Will, 1967). For each forest the needle litter was bulked and sent to FRI for chemical analysis (N, P, K, Ca, Mg). No chemical analyses were done on twigs. The analytical procedures at FRI, New Zealand, have been discussed in Section 10.2

Litter standing crop was determined by sampling the litter layer (L+F layer) once every month from January 1990 until September 1990 (8 samples at a time) and once every three months (12 samples at a time) until September, 1991. Samples were collected by randomly placing a 500 cm^2 metal plate on the litter layer and sampling everything below the plate after cutting the litter layer around the plate with scissors. The field-moist weight of each sample was determined shortly after sampling after which the sample was dried at 70 °C (see Section 11.2). The total dry weight was determined as well as the respective weights of needles, woody parts (downed stemwood after cyclone Sina, bark, branches, twigs) male flowers, cones, seeds and undergrowth material. The nutrient concentrations in needle litter (and undergrowth litter in Tulasewa forest) were determined at FRI, New Zealand, for each sampling occassion, whereas those in woody litter, male flowers and undergrowth litter were determined on bulk samples prepared from the total sample for each plot at the end of the study.

The carbon and nitrogen contents of freshly fallen needles and strongly decomposed needles, both sampled from the litter and fermentation layers in Korokula forest in September 1991, were determined to obtain C/N ratios for each of these layers. The analytical procedures have been given in Section 4.2.

Due to the limited number of samples the *"Student's"* t distribution (Spiegel, 1972) was used to decide whether observed differences in measured values between sites were statistically significant.

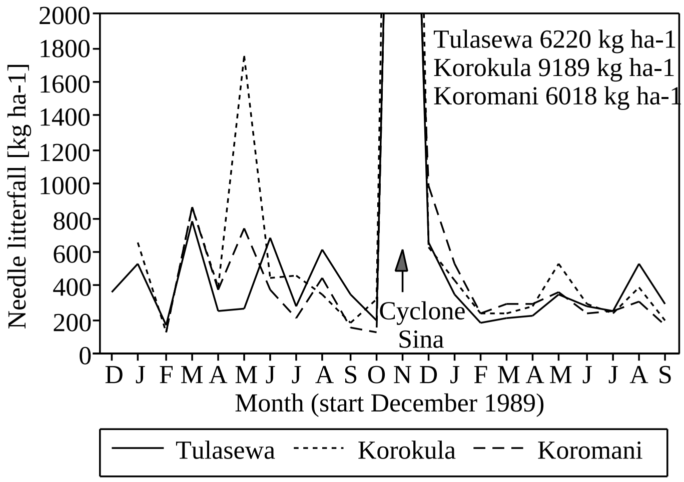


Figure 12.1: *Monthly amounts of needle fall (kg ha^{-1}) in Tulasewa, Korokula and Koromani forests. Amounts produced during the passage of cyclone Sina in November 1990 indicated in the upper right hand corner.*

12.3 Litterfall and Nutrient Content

12.3.1 Litter Production

The passage of cyclone Sina had a major impact on amounts, as well as nutrient concentrations of litterfall. Therefore pre-cyclone, cyclone and post-cyclone litterfalls will be discussed separately. The pre-cyclone data set spanned 9 (Koromani) to 11 months (Tulasewa), which of course is rather short in view of the seasonal climate. The same holds for the post-cyclone data set (9 months).

Total monthly pre-cyclone pine litterfall in the Tulasewa forest plot averaged 404($\pm$200) kg ha^{-1} (range 167–790 kg ha^{-1}). The average monthly total measured at the Korokula forest plot was significantly higher (α= 0.05) at 774($\pm$432) kg ha^{-1} (range 151–1760 kg ha^{-1}) whereas the average for the Koromani forest plot (447($\pm$261) kg ha^{-1}, range 155–970 kg ha^{-1}) was not significantly different from that of Tulasewa forest but significantly lower (α= 0.05) than that in Korokula forest. Monthly amounts of needle fall in Tulasewa, Korokula and Koromani forests are shown in Figure 12.1, whereas the actual amounts are listed in Appendix 28.1. The proportion of needle fall to the total decreased with forest age from 96% in Tulasewa forest to 72% and 85% in Korokula and Koromani forests, respectively. The passage of Cyclone Rae south of Viti Levu in March 1990 did not afflict much damage to the forest but the moderately strong winds removed dead needles formerly suspended in the canopies resulting in a peak in the needle fall (Figure 12.1). The production of litter in Tulasewa and Koromani forests remained relatively low during the dry season of 1990, indicating that these forests did not experience any water stress even after several dry weeks in April and May. However, litterfall in the Korokula forest plot peaked strongly in May 1990, suggesting that the forest experienced water stress during this dry period (Section 6.5). This difference in litter production during prolonged dry spells between forests illustrates the impact of soil properties (*e.g.* soil depth, water holding capacity) on the litter production.

The spatial variation in pre-cyclone litterfall was large as indicated by large standard deviations for monthly totals of litterfall which ranged between 41% (Koromani) and 58% (Korokula) of the average. The standard deviations for needle fall were relatively low (37–47% of average needle fall), whereas those for branches and cones were high, often exceeding the average by a factor 2–3. Therefore some confidence can be placed in the average amounts of needle fall, but the values for the other components should be treated with caution as these could be seriously in error.

No clear seasonal trends could be established from the pre-cyclone data for needle fall. However, the production of male flowers, seeds and possibly cones was strongly seasonal. Seeds were exclusively produced during the wet season, reaching a peak in March–April, whereas male flower litter production peaked during the dry season (July–August). A peak in the production of cone litter was observed during the dry season in Korokula forest, but not in Koromani forest where cone litter production was low anyway. Because cone production does not start before canopy development is completed only few trees in Tulasewa forest produced cones, which explains the low amounts observed in both pre-cyclone and cyclone litterfall.

Estimates of the annual litterfall and the relative contributions of the various components based on pre-cyclone observations are presented in Table 12.1. Annual pre-cyclone litterfall was highest in Korokula forest as a result of high production rates for woody litter as well as for needle litter during dry periods. The relatively high woody litterfall in Korokula forest may be related to the rather dense tree spacing (2*3 m) which caused interference of tree crowns within the rows of planting (asymmetric crowns) and also reduced the light conditions in the lower canopy levels compared to those in the other two forests which had different spacings (see also Section 11.3.6). The number of dead branches/twigs on the trees in Korokula forest during the pre-cyclone period was therefore higher (visual observation by the author). The high production of cone litter in Korokula forest as compared to that in Koromani forest further increased the difference in litter production. In spite of the difference in age, and therefore development phase, similar litterfall totals were observed in the Koromani and Tulasewa forest plots, probably because of the relatively low tree density in the former (Chapter 3). When litter production rates were expressed in kg tree^{-1}, however, total litter and needle litter production were lowest in the Tulasewa forest plot and highest in the Korokula forest plot.

As expected, cyclone Sina had a large impact on litter production at all sites. Amounts recorded in November 1990 were 2–4 times higher than the estimated annual pre-cyclone totals, whereas cyclone-induced needle fall exceeded estimated annual needle fall by a factor 1.5 (Table 12.1). The standard deviations for cyclone needle fall (32–46% of the average value) were similar to those of the average pre-cyclone values and the measured amounts are therefore thought to be reasonably accurate. The values obtained for the other litter components could again be seriously in error due to the large spatial variation observed for these components. This was particularly true for woody litter fall (which included parts of tree stems!) of which the standard deviations were 0.8–2.5 times the average.

Cyclone needle fall in Tulasewa forest compared well with the predicted loss of foliage from the biomass pre- and post-cyclone predictions for January 1991 (Table 11.7). In the Korokula and Koromani forest plots, where the stand density was less affected by the cyclone, measured amounts of needle fall were larger than those predicted from biomass estimations. However, because the regression equations for post-cyclone fo-

Table 12.1: *Pre-cyclone, cyclone and post-cyclone production of litterfall and its respective components in Tulasewa, Korokula and Koromani forests. Annual rates were obtained by extrapolation on a time basis which is thought to produce realistic values as clear seasonal trends were not observed for the largest litterfall component (needles). All amounts in kg ha^{-1} dry weight.*

	Needles	Wood	M. flowers	Cones	Seed	Total	Undergrowth
TULASEWA FOREST							
Pre-cyclone litter fall	4441.4	42.2	88.0	9.5	13.1	4594.2	254.3
% of total	*96.7*	*0.9*	*1.9*	*0.2*	*0.3*		
Cyclone litter fall	6874.9	14469.3	5.4	471.0	0.0	21820.6	230.8
% of total	*31.5*	*66.3*	*0.0*	*2.2*	*0.0*		
Post-cyclone litter fall	2676.7	3.6	20.1	0.0	0.0	2700.4	460.9
% of total	*99.1*	*0.1*	*0.7*	*0.0*	*0.0*		
Pre-cyclone annual total	**4845.2**	**46.0**	**96.0**	**10.4**	**14.3**	**5011.9**	**277.4**
Post-cyclone annual total	**3568.9**	**4.8**	**26.8**	**0.0**	**0.0**	**3600.5**	**614.5**
KOROKULA FOREST							
Pre-cyclone litter fall	5555.8	681.3	571.6	901.7	26.2	7736.6	127.9
% of total	*71.8*	*8.8*	*7.4*	*11.7*	*0.3*		
Cyclone litter fall	9821.7	5270.9	51.2	2948.6	0.0	18092.4	101.7
% of total	*54.3*	*29.1*	*0.3*	*16.3*	*0.0*		
Post-cyclone litter fall	2835.8	43.5	143.7	0.0	1.0	3024.0	296.4
% of total	*93.8*	*1.4*	*4.8*	*0.0*	*0.0*		
Pre-cyclone annual total	**6667.0**	**817.6**	**685.9**	**1082.0**	**31.4**	**9283.9**	**153.5**
Post-cyclone annual total	**3781.1**	**58.0**	**191.6**	**0.0**	**1.3**	**4032.0**	**395.2**
KOROMANI FOREST							
Pre-cyclone litterfall	3435.6	99.1	375.9	95.5	15.0	4021.1	544.7
% of total	*85.4*	*2.5*	*9.3*	*2.4*	*0.4*		
Cyclone litterfall	7012.3	9352.4	106.2	1390.6	0.0	17861.5	817.3
% of total	*39.3*	*52.4*	*0.6*	*7.8*	*0.0*		
Post-cyclone litterfall	2678.8	17.4	115.1	1.0	2.7	2815.0	466.4
% of total	*95.2*	*0.6*	*4.1*	*0.0*	*0.1*		
Pre-cyclone annual total	**4580.8**	**132.1**	**501.2**	**127.3**	**20.0**	**5361.5**	**726.3**
Post-cyclone annual total	**3571.7**	**23.2**	**153.5**	**1.3**	**3.6**	**3753.3**	**621.9**

liage biomass were based on data collected several months after the passage of the cyclone (Section 11.4), the difference may be explained by the rapid regeneration of needles in the intermediate period, which resulted in overestimation of the predicted pre-cyclone foliage biomass for January 1991 (Table 11.7). The loss of needles associated with the passage of cyclone Sina formed 73%, 84% and 65% of the pre-cyclone needle biomass in the Tulasewa, Korokula and Koromani forest plots, respectively (Table 11.7), illustrating the severe damage afflicted to the forest canopies by the cyclone (Lodge *et al.*, 1991). Measured amounts of woody litterfall in Tulasewa and Korokula forests were lower than those predicted from the biomass estimations, whereas measured amounts were similar to predicted amounts for Koromani forest.

Post-cyclone annual totals are presented in Table 12.1. Because the pine trees were rapidly generating new foliage and because needle biomass was very low anyway, post-cyclone monthly averages of litterfall were much lower than the corresponding pre-cyclone averages. Post-cyclone monthly amounts of litterfall were not significantly different between the Tulasewa, Korokula and Koromani forest plots at 297(±98), 336(±112) and 313(±97) kg ha^{-1}, respectively. The litterfall composition had also changed with the proportion of needle fall increasing to 95–99% of the total, with corresponding decreases in the proportions of other components. Most of the cones and dead branches had been removed from the canopy during the cyclone, reducing woody and cone litterfall to almost zero (Table 12.1).

The litterfall produced by the undergrowth in the three forest plots consisted for a large part of grass leaves and seeds and the actual litter production by the undergrowth was severely underestimated because dead grass stalks often remained erect and did not end up in the littertraps. Pre-cyclone litter production by the undergrowth in the Tulasewa forest plot, which was heavily dominated by *Pennisetum polystachyon* grass may be approximated by the production rates for grass presented in Table 10.1, *i.e.* about 6.5 t ha^{-1}. Taking the latter value at face value this would imply that production of litter by the undergrowth at this site was at least as high as that by the tree storey for the pre-cyclone period. The improved light conditions within the forest after the cyclone event in November 1990 caused a two-fold increase in measured litter production of the undergrowth, and the actual production may well have been much higher than that of the forest. Due to the low undergrowth biomass in the Korokula forest plot, and the low proportion of grass in the undergrowth at Koromani forest, the underestimates presented for these forests should not lead to serious errors in the overall forest nutrient budgets. A more than two-fold increase in undergrowth litterfall was also observed in the Korokula forest plot after cyclone Sina, but not in Koromani forest which already had a more open character due to previous cyclone damage (Section 3.4).

12.3.2 Nutrient Concentrations in Litterfall

Average nutrient concentrations in needle fall and in bulk samples of woody litterfall (stemwood, branches, twigs and cones), male flower litterfall (if present) and undergrowth litterfall in Tulasewa, Korokula and Koromani forests are presented in Table 12.2, whereas monthly needle fall concentrations are given in Appendix 28.1. Concentrations in needle fall were fairly similar to those of dead and yellow needles collected from within the crowns of trees sampled for biomass (Tables 11.8, 11.9 and 11.10), which suggests that losses of nutrients in the period between needle fall and sampling were negligible. However, concentrations of P in needle fall in Korokula forest were much higher than in dead needles collected from within the crowns.

Fluctuations in needle fall nutrient levels showed no distinct seasonal patterns, although Mg levels reached a maximum at the end of the wet season (April–May) in both the Korokula and Koromani forest plots (Appendix 28.1).

Monthly concentrations of N, K and Ca in needle fall in Tulasewa forest are shown in Figure 12.2. Trends for P and Zn were similar to that of N, whereas the trends for Mg, B and Mn were similar to that of Ca, although less pronounced. Seasonal variations in needle fall nutrient levels in Korokula and Koromani forests were comparable to those shown for Tulasewa forest (see Appendix 28.1). Clearly, cyclone Sina had a much larger impact on needle fall nutrient levels than any seasonal trend might have had. Ca levels in post-cyclone needle fall were lower than those in pre-cyclone needle fall, whereas N, P, K, Mg, Mn and Zn levels were all higher than in pre-cyclone needle fall until four months after the event when nutrient concentrations returned to pre-cyclone levels (Figure 12.2). These changes in concentrations suggest that during this period relatively young needles died and fell without complete retranslocation of

Table 12.2: *Average nutrient concentrations in pre-cyclone, cyclone needle fall and post-cyclone needle fall, and in bulk samples of woody litter fall, male flower and undergrowth litterfall in Tulasewa, Korokula and Koromani forests. Concentrations for macro- and micronutrients in % and ppm respectively.*

	N	P	K	Ca	Mg	B	Mn	Zn
TULASEWA FOREST								
Dec'89-Oct'90, pre-cyclone needle fall								
Weighted average	0.389	0.016	0.092	0.887	0.200	9.4	563	26
Arithmetric mean (n=11)	0.387	0.016	0.096	0.878	0.200	9.5	581	27
Standard deviation	0.039	0.004	0.024	0.064	0.012	0.9	69	3
Nov'90-Dec'90, cyclone needle fall								
Weighted average (n=2)	0.670	0.069	0.314	0.610	0.193	8.0	487	24
Jan'91-Sep'91, post-cyclone needle fall								
Weighted average (n=9)	0.436	0.035	0.106	0.823	0.223	10.1	647	30
Arithmetic mean	0.444	0.035	0.107	0.828	0.224	10.1	636	30
Standard deviation	0.107	0.011	0.035	0.070	0.015	0.8	7	3
Woody litter fall (bulk)	0.199	0.028	0.172	0.163	0.061			
Undergrowth litter fall (bulk)	0.668	0.050	0.579	0.305	0.252			
KOROKULA FOREST								
Jan'90-Oct'90, pre-cyclone needle fall								
Weighted average	0.312	0.012	0.074	0.780	0.327	13.6	378	14
Arithmetic mean (n=10)	0.321	0.013	0.072	0.784	0.317	13.8	392	14
Standard deviation	*0.043*	*0.006*	*0.022*	*0.069*	*0.021*	*1.6*	*44*	*2*
Nov'90-Dec'90, cyclone needle fall								
Weighted average (n=2)	0.772	0.049	0.226	0.562	0.309	14.9	380	16
Jan'91-Sep'91, post-cyclone needle fall								
Weighted average	0.482	0.096	0.084	0.690	0.340	14.4	381	21
Arithmetic mean (n=9)	0.471	0.091	0.082	0.694	0.338	14.4	400	21
Standard deviation	*0.131*	*0.040*	*0.015*	*0.042*	*0.015*	*0.6*	*100*	*3*
Woody litter fall (bulk)	0.394	0.033	0.156	0.200	0.101			
Male flower fall (bulk)	0.851	0.064	0.141	0.161	0.147			
Undergrowth litter fall (bulk)	1.092	0.082	0.790	0.993	0.622			
KOROMANI FOREST								
Feb'90-Oct'90, pre-cyclone needle fall								
Weighted average	0.342	0.011	0.099	0.684	0.206	10.2	607	16
Arithmetic mean (n=9)	0.334	0.011	0.095	0.683	0.201	10.7	624	19
Standard deviation	*0.043*	*0.002*	*0.014*	*0.050*	*0.021*	*1.9*	*66*	*9*
Nov'90-Dec'90, cyclone needle fall								
Weighted average (n=2)	0.807	0.048	0.268	0.518	0.184	10.9	612	21
Jan'91-Sep'91, post-cyclone needle fall								
Weighted average	0.520	0.021	0.110	0.658	0.185	11.3	735	25
Arithmetic mean (n=9)	0.506	0.020	0.105	0.656	0.184	11.6	748	25
Standard deviation	*0.119*	*0.008*	*0.021*	*0.036*	*0.007*	*1.1*	*66*	*6*
Woody litterfall	0.314	0.029	0.121	0.324	0.093			
Male flower fall (bulk)	0.813	0.057	0.126	0.186	0.133			
Undergrowth litter fall	1.030	0.048	0.269	1.203	0.515			

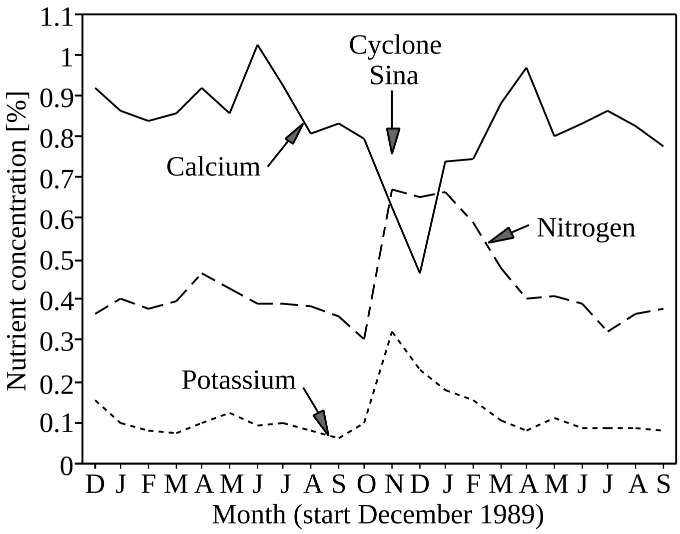


Figure 12.2: *Concentrations of N, K and Ca in monthly samples of needle fall in Tulasewa forest.*

their nutrients. The differences in means of pre- and post-cyclone concentrations in needle fall for each site are shown in Table 12.3 together with their significance levels.

Similar changes in needle fall nutrient concentrations were observed in a *Pinus caribaea* plantation forest at Humpty Doo, Queensland, after a wildfire defoliated the stand in 1978 (Maggs, 1981).

Significant differences were observed between sites (Table 12.3), possibly reflecting differences in site quality. Pre-cyclone levels of N, P, Ca and Zn were highest in the Tulasewa forest plot whereas Mg and B levels were highest in Korokula forest. K and Mn concentrations were highest in the Tulasewa and Koromani forest plots, respectively. No significant differences were found for the N concentrations in needle fall between the sites in the post-cyclone period. Ca and Zn levels in needle fall were again highest in the Tulasewa forest plot, whereas P, Mg and B levels were highest in the Korokula forest plot and Mn was highest in the Koromani forest plot.

12.3.3 Nutrient Returns to the Forest Floor via Litterfall

Amounts of nutrients deposited onto the forest floor in litterfall in the Tulasewa, Korokula and Koromani forest plots during the study are given in Tables 12.4 – 12.6, respectively. Needle fall accounted for 97.4% of the total return of K to the forest floor in the Tulasewa forest plot, and for 99.7% of that for Ca with intermediate values for N, P and Mg. In the older forests where woody litterfall formed a larger fraction of total litterfall (Table 12.1), needle fall still accounted for a large proportion of the annual return of nutrients to the forest floor. In the Korokula forest plot needle fall accounted for 43% of the annual return of P and for 91% of that for Ca with intermediate values for N (61%), K (56%) and Mg (88%). Similar values were observed in Koromani forest where needle fall accounted for 58% of the pre-cyclone annual return of P and for 91%

Table 12.3: *Significance levels for within- and between-site differences in mean nutrient concentrations in pre- and post-cyclone needle litterfall.*

Difference in means of needle fall	N	P	K	Ca	Mg	B	Mn	Zn
Tulasewa pre- <> post-cyclone	<*	<***	ns	>*	<***	<*	<**	<**
Korokula pre- <> post-cyclone	<**	<***	ns	>***	<***	<**	ns	<***
Koromani pre- <> post-cyclone	<***	<***	ns	ns	>**	ns	<***	<*
Pre-cyclone Tulasewa <> Korokula	>***	>*	>**	>***	<***	<***	>***	>***
Pre-cyclone Tulasewa <> Koromani	>***	>***	ns	>***	ns	<*	ns	>**
Pre-cyclone Korokula <> Koromani	ns	ns	<***	>***	>***	>***	<***	<*
Post-cyclone Tulasewa <> Korokula	ns	<***	>**	>***	<***	<***	>***	>***
Post-cyclone Tulasewa <> Koromani	ns	>***	ns	>***	>***	<***	<***	>**
Post-cyclone Korokula <> Koromani	ns	>***	<***	>**	>***	>***	<***	<**

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

Table 12.4: *Amounts of nutrients (kg ha^{-1}) returned to the forest floor in litterfall in the Tulasewa forest plot.*

	N	P	K	Ca	Mg	B	Mn	Zn
Dec'89-Oct'90, pre-cyclone needle fall	17.27	0.69	4.09	39.38	8.86	0.04	2.50	0.12
Nov'90-Dec'90, cyclone needle fall	46.07	4.78	21.60	41.93	13.29	0.05	3.35	0.17
Jan'91-Sep'91, post-cyclone needle fall	11.68	0.93	2.83	22.03	5.98	0.03	1.73	0.08
Dec'89-Oct'90, pre-cyclone woody litter fall	0.13	0.02	0.11	0.11	0.04			
Nov'90-Dec'90, cyclone woody litter fall	29.73	4.18	25.70	24.35	9.11			
Jan'91-Sep'91, post-cyclone woody litter fall	0.01	0.00	0.01	0.01	0.00			
Total in pine litter fall	**104.89**	**10.60**	**54.33**	**127.81**	**37.28**			
Total in cyclone pine litter fall	**75.80**	**8.96**	**47.29**	**66.29**	**22.40**			
Pre-cyclone annual total pine litter fall	**18.98**	**0.78**	**4.58**	**43.08**	**9.71**			
Dec'89-Oct'90, pre-cyclone undergrowth litter fall	1.70	0.13	1.47	0.78	0.64			
Nov'90-Dec'90, cyclone undergrowth litter fall	1.54	0.12	1.34	0.70	0.58			
Jan'91-Sep'91, post-cyclone undergrowth litter fall	3.08	0.23	2.67	1.41	1.16			
Total in undergrowth litter fall	**6.32**	**0.47**	**5.48**	**2.89**	**2.38**			
Pre-cyclone annual total	**1.85**	**0.14**	**1.61**	**0.85**	**0.70**			

Table 12.5: *Amounts of nutrients (kg ha^{-1}) returned to the forest floor in litterfall in the Korokula forest plot.*

	N	P	K	Ca	Mg	B	Mn	Zn
Jan'90-Oct'90, pre-cyclone needle fall	17.36	0.66	4.11	43.34	18.15	0.08	2.10	0.08
Nov'90-Dec'90, cyclone needle fall	75.81	4.79	22.16	55.16	30.34	0.15	3.73	0.15
Jan'91-Sep'91, post-cyclone needle fall	13.66	2.73	2.39	19.57	9.65	0.04	1.08	0.06
Jan'90-Oct'90, pre-cyclone woody litter fall	6.24	0.52	2.47	3.17	1.60			
Nov'90-Dec'90, cyclone woody litter fall	32.38	2.71	12.82	16.44	8.30			
Jan'91-Sep'91, post-cyclone woody litter fall	0.17	0.01	0.07	0.09	0.04			
Jan'90-Oct'90, pre-cyclone male flower fall	4.86	0.37	0.81	0.92	0.84			
Nov'90-Dec'90, cyclone male flower fall	0.44	0.03	0.07	0.08	0.08			
Jan'91-Sep'91, post-cyclone male flower fall	1.22	0.09	0.20	0.23	0.21			
Total in pine litter fall	**152.14**	**11.91**	**45.11**	**139.00**	**69.21**			
Total in cyclone pine litter fall	**108.63**	**7.53**	**35.06**	**71.68**	**38.72**			
Pre-cyclone annual total pine litter fall	**34.15**	**1.85**	**8.86**	**56.92**	**24.70**			
Jan'90-Oct'90, pre-cyclone undergrowth litter fall	1.40	0.10	1.01	1.27	0.80			
Nov'90-Dec'90, cyclone undergrowth litter fall	1.11	0.08	0.80	1.01	0.63			
Jan'91-Sep'91, post-cyclone undergrowth litter fall	3.24	0.24	2.34	2.94	1.84			
Total in undergrowth litter fall	**5.74**	**0.43**	**4.16**	**5.22**	**3.27**			
Pre-cyclone annual total	**1.68**	**0.13**	**1.21**	**1.52**	**0.95**			

of that for Mg with intermediate values for Ca (71%), N (75%) and K (83%).

The estimated annual returns of N, P and K in pre-cyclone litterfall were much smaller (9–25%, 25–31% and 13–23% in Tulasewa, Korokula and Koromani forests respectively) than the corresponding amounts released in cyclone induced litterfall. Estimated annual returns of Ca in pre-cyclone litterfall in the three forests were 65%, 79% and 46% of those in the litterfall associated with cyclone Sina, respectively, with corresponding values of 43%, 64% 45% for Mg. In Puerto Rico, nutrient returns in litterfall during the passage of hurricane Hugo also equalled or exceeded the mean annual nutrient returns in litterfall in natural rain forests for years without hurricanes (Lodge *et al.*, 1991). Because cyclones of the intensity of cyclone Sina pass regularly over the forests in Viti Levu (once every 2–3 years, Section 2.4.4) the amounts of N, P and K, and to a lesser extent of Mg and Ca, in litterfall during a cyclone event may well be similar to the return of the total amounts recorded during the period between two cyclones. However, not all forests will be equally affected by the same cyclone due to differences in exposure to the wind field (Walker, 1991), and it is therefore difficult to predict the total return of nutrients to the forest floor over a rotation period for the Fijian situation.

As indicated, the return of nutrients to the forest floor in undergrowth litter was underestimated in all plots. However, as the undergrowth biomass in the forests plots did not show a major change during the present study (visual observation), amounts of nutrients released from undergrowth litter are likely to be used by the undergrowth during the following wet season. The undergrowth biomass showed a sharp decrease after canopy closure, somewhere between age 6 and 11 (Figure 11.7). During this period the release of nutrients from undergrowth litter may be expected to exceed the uptake.

Table 12.6: *Amounts of nutrients (kg ha^{-1}) returned to the forest floor in litterfall in the Koromani forest plot.*

	N	P	K	Ca	Mg	B	Mn	Zn
Feb'90-Oct'90, pre-cyclone needle fall	11.75	0.37	3.41	23.48	7.09	0.03	2.09	0.06
Nov'90-Dec'90, cyclone needle fall	56.61	3.35	18.82	36.30	12.91	0.08	4.29	0.15
Jan'91-Sep'91, post-cyclone needle fall	13.93	0.57	2.94	17.61	4.94	0.03	1.97	0.07
Feb'90-Oct'90, pre-cyclone woody litter fall	0.61	0.06	0.24	0.63	0.18			
Nov'90-Dec'90, cyclone woody litter fall	33.73	3.12	13.00	34.81	9.99			
Jan'91-Sep'91, post-cyclone woody litter fall	0.06	0.01	0.02	0.06	0.02			
Feb'90-Oct'90, pre-cyclone male flower fall	3.06	0.21	0.47	0.70	0.50			
Nov'90-Dec'90, cyclone male flower fall	0.86	0.06	0.13	0.20	0.14			
Jan'91-Sep'91, post-cyclone male flower fall	0.94	0.07	0.15	0.21	0.15			
0.0								
Total in pine litter fall	**121.54**	**7.80**	**39.18**	**114.00**	**35.93**			
Total in cyclone pine litter fall	**91.21**	**6.52**	**31.96**	**71.30**	**23.05**			
Pre-cyclone annual total pine litter fall	**20.55**	**0.85**	**5.49**	**33.09**	**10.36**			
Feb'90-Oct'90, pre-cyclone undergrowth litter fall	5.61	0.26	1.47	6.55	2.81			
Nov'90-Dec'90, cyclone undergrowth litter fall	8.42	0.39	2.20	9.83	4.21			
Jan'91-Sep'91, post-cyclone undergrowth litter fall	4.80	0.22	1.25	5.61	2.40			
Total in undergrowth litter fall	**18.83**	**0.88**	**4.92**	**22.00**	**9.42**			
Pre-cyclone annual total	**7.48**	**0.35**	**1.95**	**8.74**	**3.74**			

12.4 Litter Decomposition

Decomposition rates of needles and twigs and the release of nutrients from decomposing needles were studied in the Tulasewa, Korokula and Koromani forest plots using the mesh-bag technique. In addition, litter turnover rates (fractional loss weights, K_L) were calculated as the ratio of pre-cyclone needle litterfall (Table 12.1) to corresponding amounts of needle litter on the forest floor (Table 12.7) for the older forests where the litter layer had presumably reached a steady state, This resulted in pre-cyclone K_L-values of 0.62 and 0.41 for needle litter in the Korokula and Koromani forest plots respectively. These values lie in between those obtained by Egunjobi and Onweluzo (1979; K_L about 0.3) and Cuevas *et al.* (1991; $K_L = 0.9$–1.5) for *Pinus caribaea* litter in stands in Nigeria and Puerto Rico, respectively.

Total C decreased from 52.5% in freshly fallen needles in the L-layer to 49.9% in severely decomposed needles in the underlying F-layer in the Korokula forest plot. Corresponding N levels increased from 0.50% to 0.97%, implying a decrease in C/N ratio from 105 in fresh needle litter to 52 in heavily decomposed needles.

The rates and patterns of decomposition of both needles and twigs were roughly similar between sites. Needle decomposition rates were highest during the wet season of 1990, shortly after incubation, with observed mass losses of about 20% of the initial mass within two months after incubation. Decomposition slowed down somewhat during the following dry season but increased again during the wet season of 1991 (Figure 12.3).

Needle decomposition rates were similar in the Tulasewa and Korokula forest plots with equal first year mass losses of 48% and slightly lower in Koromani forest where 43% of the initial mass was lost after one year. At 600 days after incubation 28($\pm$7)% of

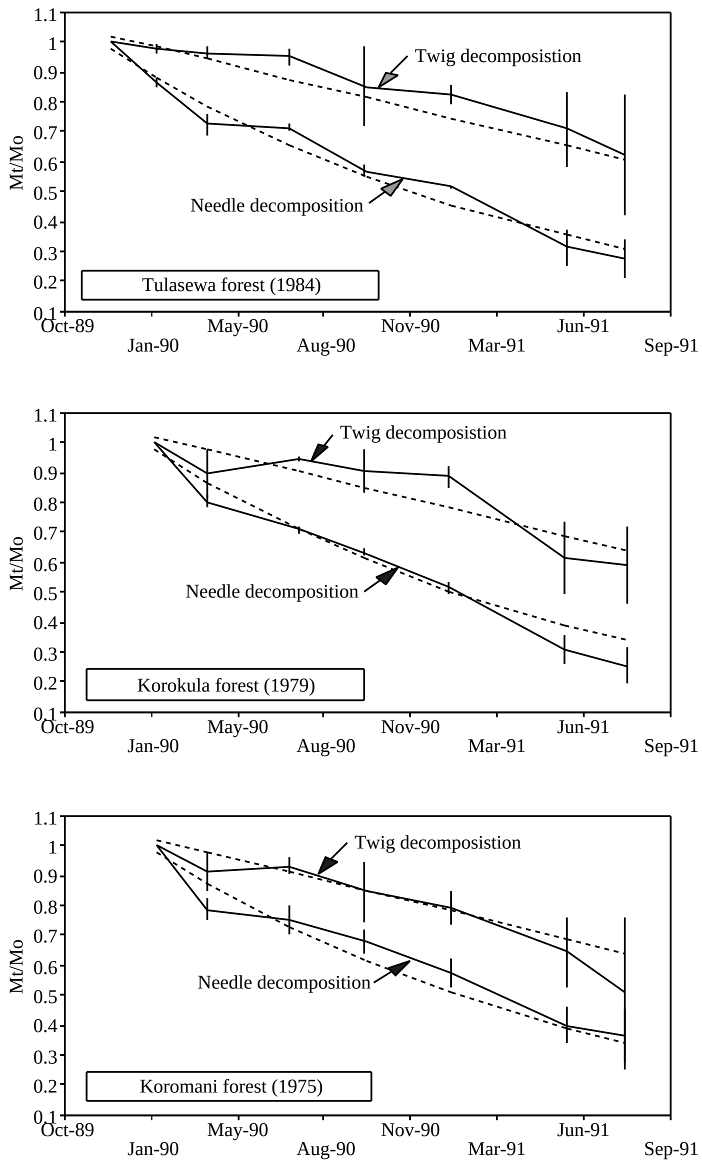


Figure 12.3: *Needle and twig decomposition rates in the Tulasewa, Korokula and Koromani forest plots, expresssed as the ratio of mass at time t after incubation* (M_t) *to that at incubation* (M_0). *Dotted line represents a fitted curve using an exponential decay function.*

the initial needle mass was left on the forest floor in the Tulasewa forest plot, whereas in the Korokula and Koromani forest plots, respectively, 25(±6)% and 37(±9)% of the initial needle mass was left after 550 days. These differences must be attributed to differences in soils, as the climatic conditions and needle litter quality were fairly similar at all sites. The first year mass losses observed during this study were similar to those found in by Gunadi and Verhoef (1993) in stands of *Pinus merkusii* in Central Java.

Twig decomposition was much slower than that of needles (Figure 12.3) and exhibited a different pattern with little mass loss during the first year after incubation (11–21%) and increased losses in the following period (20–30%) mass loss in 7 months.

An exponential decay model (Witkamp and Olson, 1963):

$$M_t/M_0 = a \exp^{-b \cdot t} \tag{12.1}$$

was fitted to the grouped needle decomposition data (n=22) where M_t/M_0 represented the needle mass fraction remaining at time t (in months) after incubation. Non-linear regression analysis on the needle decomposition data for all plots (n=22) resulted in values of 0.976(±0.022) and 0.059(±0.003) for a and b respectively, with a coefficient of determination of 0.96. The exponential decay model did not describe the decay of twigs accurately so a linear model ($M_t/M_0 = a + b \cdot t$) was used instead. Linear regression analysis gave values of 1.020(±7.952) and -0.021(±0.000) for the intercept and slope respectively with a coefficient of determination of 0.85. The predicted decomposition rates have been shown in Figure 12.3) as dotted lines.

The corresponding changes in nutrient concentrations (C_t) and contents over the duration of the study are shown in Figure 12.4. Concentrations of K, and to a lesser extent P, showed a sharp drop in the first 2–3 months after incubation, possibly as a result of leaching, and remained fairly constant afterwards (Figure 12.4A,B and C), indicating that these nutrients are then removed parallel to the mass loss. At the end of the study 84–93% of K and 44%–76% of P had been released, with the lower values observed for the Koromani forest plot.

At the Tulasewa and Korokula forest plots N concentrations increased steadily from initial levels of 0.8% and 0.9% to a critical value of 1.6–1.7% after 16 months, and showed a slight decrease thereafter (Figure 12.4A and B). Total N increased throughout the study in Koromani forest from an initial level of 1.0% to a critical N concentration of 1.9% at the end of the study when the increase levelled off (Figure 12.4C). The corresponding C/N ratio was calculated assuming that the concentration of total C remained constant at 50% during the decomposition. This would result in a decrease of the C/N ratio from initial values ranging between 50 and 64 to values ranging between 27 and 32 at the end of the study (Figure 12.5). Figures 12.4D–F show that N remained immobilized, with the release amounting to less than 20% of the initial N content during the first year, until the critical concentration was reached and N was released at a higher rate. Some 32% (Koromani forest) to 56% (Korokula forest) of N had been released by August 1991.

Concentrations of Mg decreased slightly in the first months (Figures 12.4A–C), possibly as a result of leaching, and increased from then onwards to 150% of their initial concentration (0.25–0.32%). As such Mg became increasingly immobilized during the process and some 45–62% of the total Mg content was released over the 550–600 day period. A similar pattern was observed for the concentration of Ca in the needle litter, which showed a 167% (Tulasewa) to 195% (Koromani) increase compared to the initial concentration (0.7–1.1%) over the 18 months. The release of Ca after

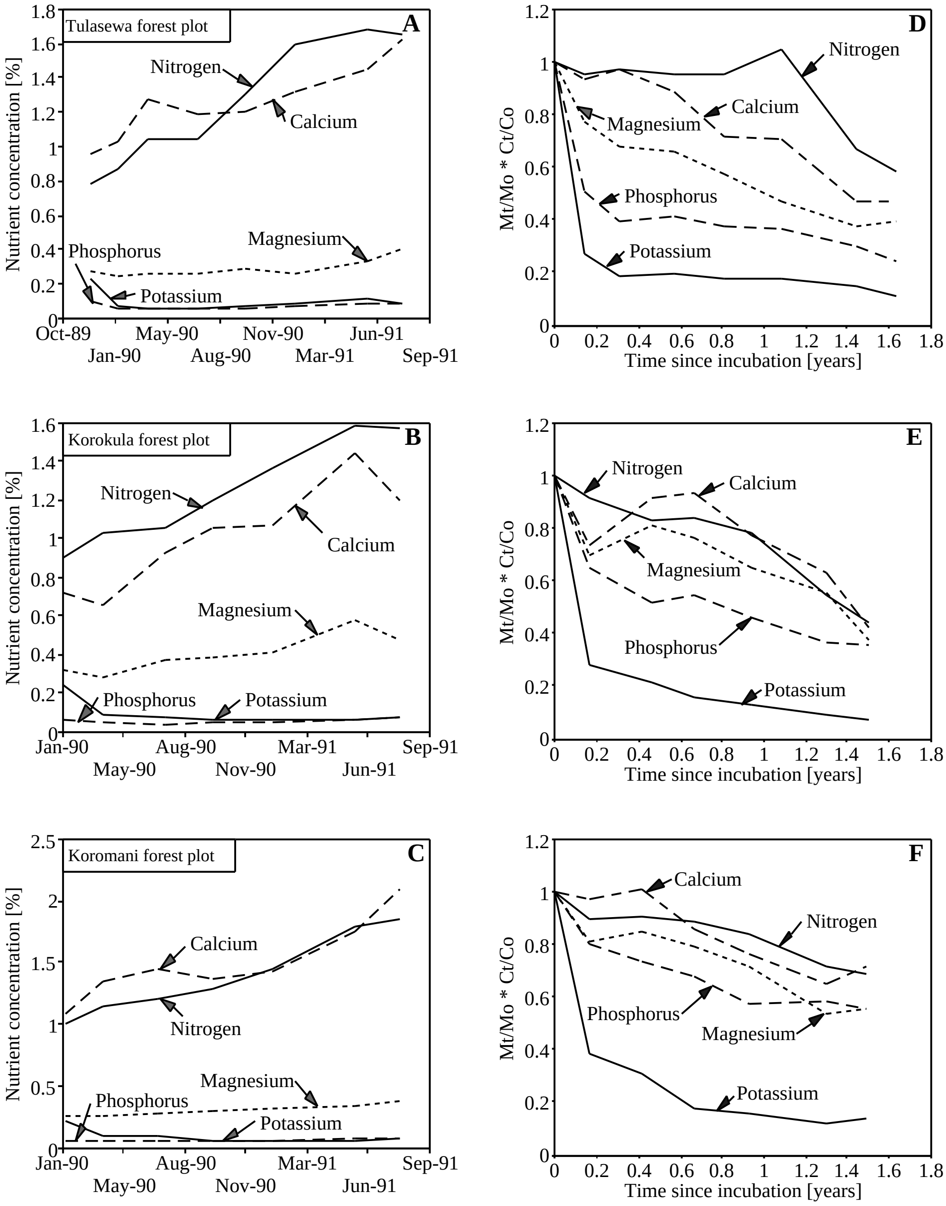


Figure 12.4: *(A,B,C) Changes in needle litter nutrient concentrations and (D,E,F) relative nutrient contents, expressed as a fraction of the initial nutrient content, during the decomposition study in the Tulasewa, Korokula and Koromani forest plots.*

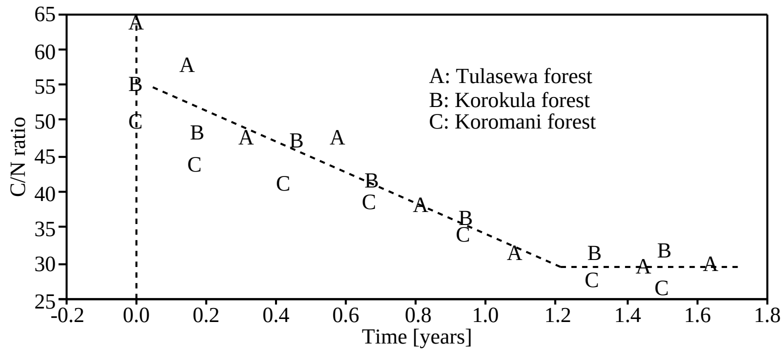


Figure 12.5: *Changes in C/N ratio during decomposition of pine needle litter assuming a constant value of 50% for the concentration of total C.*

18 months was much higher in the Tulasewa and Korokula forest plots than in the Koromani forest plot with 53–58% released at the former and only 29% released at the latter (Figures 12.4D–F).

The concentrations of N, P and K in the green–yellow needles sampled from within the lower parts of the tree crowns (*i.e.* before natural abscission) for the litter decomposition experiment were higher than those observed in pre-cyclone needle fall (see Table 12.2), whereas Ca and Mg concentrations were slightly lower. This indicated that retranslocation (N, P, K) had not finished before needles were sampled. The lower concentrations of N, P and K in needle fall may also have arisen from the fact that abscissed needles are often intercepted lower down in the tree crowns and undergrowth vegetation and may remain suspended for considerable periods of time during which time it is likely that some changes in nutrient concentrations will occur (*e.g.* leaching of K, P and possibly N), before the needles finally reach the forest floor. The higher N concentration in the above samples may also have influenced the release of this element during the decomposition experiment as the initial C/N ratio was much lower (52–64) than that in needle litterfall (129–160). However, the C/N ratio in decomposed needles sampled from the fermentation layer in Korokula forest was also higher (52) than that of needle litter at the end of the decomposition experiment (30) suggesting that the critical N concentration may depend on the initial nutrient concentrations in the needle litter. As such it would be possible to apply the results of the present study to litter with lower initial concentrations. The concentrations of N, P and K in cyclone needle fall were similar to those of needles sampled for the litter decomposition experiment and the results of the experiment will therefore certainly be representative for post-cyclone needle decomposition.

12.5 Litter Standing Crop

12.5.1 Mass and Composition of the Litter Layer

The amount of litter on the forest floor depends on the interplay between litter production and the decomposition both of which have been discussed in the previous sections. The temporal variations in litter standing crop at the Tulasewa, Korokula

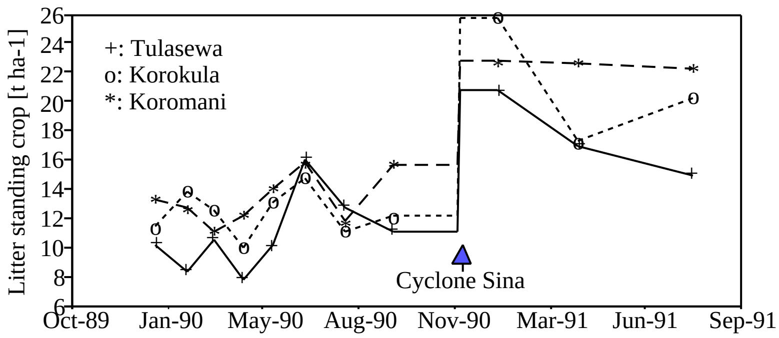


Figure 12.6: *Litter standing crop in the Tulasewa, Korokula and Koromani forest plots.*

and Koromani forest plots are shown in Figure 12.6. Seasonal patterns were fairly similar for the three plots with relatively low amounts during the wet season, coinciding with high decomposition rates (Section 12.4), and higher amounts during the dry season, when decomposition slowed down.

The litter layer mass during the wet season of 1990 in the Tulasewa forest plot was comparable to that in the Nabou grassland plot (Section 10.3) and ranged between 7725(±2686) and 10550(±3582) kg ha^{-1}. The mass increased at the start of the dry season, reaching a maximum of 16065(±9124) kg ha^{-1} after two dry months in June 1990, and decreased again gradually during the wetter months of August and September to 11055(±2222) kg ha^{-1}. Amounts of litter on the forest floor were significantly higher in the Korokula (α= 0.10) and Koromani (α= 0.05) forest plots (Figure 11.7), with no significant differences between the latter two. During the wet season of 1990 litter layer mass ranged from 9955(±1741) kg ha^{-1} to 13863(±2356) kg ha^{-1}) in the Korokula forest plot and from 11050(±3388) kg ha^{-1} to 13245(±4293) kg ha^{-1} in the Koromani forest plot. Litter standing crop peaked at 14778(±2380) kg ha^{-1}) in June at the Korokula forest plot, followed by a gradual decrease during the dry season to 10483(±1734) kg ha^{-1} in September. Similarly, a maximum of 15715(±7553) kg ha^{-1} was observed in June at the Koromani forest plot (Figure 12.6). Measured amounts of needle litter and undergrowth litter (Tulasewa forest only) are listed in Appendix 28.2.

After the passage of cyclone Sina in November 1990 amounts of litter standing crop at the Tulasewa, Korokula and Koromani forest plots increased dramatically to 20702(±5339) (excluding fallen trees), 25750(±7103) and 22688(±4882) kg ha^{-1}, respectively. Decomposition of the freshly fallen needles reduced the needle mass with 2900 (Tulasewa) to 4800 kg ha^{-1} (Koromani) in the period January–August 1991. Average amounts of pre- and post-cyclone litter standing crop in the three plot are given in Table 12.7. It was not possible to include fallen tree stems in the Tulasewa forest plot after the cyclone event and the post-cyclone amounts of litter on the forest floor therefore reflect amounts of needles and small woody components (*e.g.* branches, twigs and cones) only. The actual amount of total litter (including stems) was estimated at 30000–45000 kg ha^{-1} in December 1990 using the equations from Section 11.4.

The composition of the litter layer changed between age 6 and 11, reflecting the sharp decrease in undergrowth biomass. The litter layer in the Tulasewa forest plot consisted for 62% of grass litter, whereas needles accounted for 28% of the total, ranging from 1250(±1297) kg ha^{-1} in February to 5451(±1779) kg ha^{-1} in June 1990. Severely decomposed and burned tree stems of the forest that was destroyed and burned in 1983 were still present at the start of the study and formed the bulk of woody material in the litter layer. This material was included in the litter layer samples collected.

The proportion of undergrowth litter was much lower in the older forests, ranging from 10% of the total in the Korokula forest plot to 19% in Koromani forest plot (Table 12.7). This corresponded with an increase in the proportion of needles to 72% of the total in Korokula forest and 62% in Koromani forest. The pre-cyclone forest floor needle mass in the Korokula and Koromani forest plots varied between 7138(±1201)–11033(±1976) and 7217(±3225)–10679(±1527) kg ha^{-1}, respectively.

The high litterfall associated with cyclone Sina caused an increase in the proportion of needles from 28% before the event to 43% of the total in the post-cyclone litter layer (excluding downed stemwood) in the Tulasewa forest plot, with a corresponding decrease in the proportion of undergrowth to 34% of the total. The proportions of needles in the post-cyclone litter layers in Korokula and Koromani forest plots decreased respectively to 55% and 48%, with corresponding increases in woody litter (branches, twigs and cones) from 15% and 16% to 36% and 32% of the total.

12.5.2 Nutrient Concentrations of Litter

Average pre- and post-cyclone concentrations of nutrient in the various components of the litter layers (needles, undergrowth material, branches, cones, male flowers) in the Tulasewa, Korokula and Koromani forest plots are given in Table 12.8, whereas the analytical data is listed in Appendix 28.2. Concentrations of N, P, K and Mg were highest in undergrowth litter and male flowers, followed by those in needles, cones and wood. The concentration of Ca was highest in needles and lowest in cones and wood.

Differences in mean pre- and post-cyclone concentrations in needle litter for each site are shown in Table 12.9 together with their significance levels. Significant increases were observed in the concentrations of N and P at all sites after the passage of cyclone Sina, whereas concentrations of Mg and B remained fairly unchanged. The Ca concentration decreased significantly in the Tulasewa forest plot, but not in the other forest plots, whereas K concentrations increased in both the Tulasewa and Koromani forest plots. As shown in Table 12.9 there were significant differences between the sites. Pre-cyclone levels of N, Mg and B were highest in the Korokula forest plot, the concentration of K was highest in the Koromani forest plot and those of Ca and Zn were highest in the Tulasewa forest plot. P levels were lowest in the Koromani forest plot whereas Mn levels were lowest in Korokula forest. Post-cyclone levels of N and K in needle litter were not significantly different between sites.

Linear regression analysis was used to see whether the quality of pre-cyclone needle fall influenced the quality of the litter layer. The results indicated that average pre-cyclone concentrations of K, Ca, Mg B, Mn and Zn in needle fall were positively correlated with those in needle litter with coefficients of determination between 0.90 (K) and 1.00 (Zn), whereas the N concentration in needle fall was negatively correlated with that in needle litter with a coefficient of determination of 0.92. The concentration of P in needle fall was poorly correlated with that in needle litter with a coefficient of determination of 0.25.

Table 12.7: *Pre- and post-cyclone amounts and distribution of litter on the forest floors (kg ha^{-1}) in the Tulasewa, Korokula and Koromani forest plots.*

	Total	Needles	Wood	M. flowers	Cones	Seed	Undergrowth
TULASEWA FOREST (Planted 1984)							
Jan'90-Sep'90							
Pre-cyclone mean (n=7)	10561	2951	607	52	389	3.2	6558
Standard deviation	2504	1230	666	44	954	5.5	882
% of total		27.9	5.7	0.5	3.7	0.0	62.1
Jan'91-Jul'91							
Post-cyclone mean (n=3)	17494	7437	2967	47	1100	5.0	5938
Standard deviation	2407	1208	1035	29	457	7.1	1591
% of total		42.5	17.0	0.3	6.3	0.0	33.9
KOROKULA FOREST (Planted 1979)							
Jan'90-Sep'90							
Pre-cyclone mean (n=7)	12493	9030	704	315	1184	2.1	1257
Standard deviation	*1482*	*1284*	*368*	*84*	*483*	*3.6*	*700*
% of total		*72.3*	*5.6*	*2.5*	*9.5*	*0.0*	*10.1*
Jan'91-Jul'91							
Post-cyclone mean (n=3)	21097	11539	4185	111	3352	2.2	1908
Standard deviation	*3519*	*2369*	*855*	*64*	*1005*	*2.1*	*552*
% of total		*54.7*	*19.8*	*0.5*	*15.9*	*0.0*	*9.0*
KOROMANI FOREST (Planted 1975)							
Jan'90-Sep'90							
Pre-cyclone mean (n=7)	13511	8434	1268	249	943	0.4	2617
Standard deviation	*1626*	*1078*	*922*	*48*	*575*	*0.9*	*1014*
% of total		*62.4*	*9.4*	*1.8*	*7.0*	*0.0*	*19.4*
Jan'91-Jul'91							
Post-cyclone mean (n=3)	22531	10871	4670	141	2604	4.4	4241
Standard deviation	*193*	*1966*	*2157*	*61*	*1725*	*5.2*	*1134*
% of total		*48.2*	*20.7*	*0.6*	*11.6*	*0.0*	*18.8*

As the undergrowth vegetation in Tulasewa forest was similar to the grassland vegetation, pre-cyclone concentrations in undergrowth litter (Table 12.8) were comparable to those observed in grassland litter (Table 10.3). Concentrations of all macronutrients in the undergrowth litter of the Tulasewa forest plot increased after the cyclone event. The reason for this is obscure, but it is suggested that the large amounts of nutrients returned to the forest floor in the pine litterfall increased the availability of nutrients for the grass, resulting in a lower need for retranslocation of nutrients before dieback.

12.5.3 Nutrient Content of Litter

The immobilization of nutrients in the litter layer reflects both differences in the litter layer mass and composition as well as nutrient concentrations of the respective components. Average pre- and post-cyclone nutrient contents of the litter layers in the Tulasewa, Korokula and Koromani forest plots are given in Tables 12.10–12.12, respectively. In Tulasewa forest N, P, K and Mg in undergrowth litter accounted for 58–69% of total pre-cyclone litter layer nutrient content, whereas Ca accounted for 34% of the total. In the older forests most of the nutrients were stored in needle litter. However, in spite of the low undergrowth biomass (compared to that of

Table 12.8: *Averages and standard deviations (foliage only) of pre- and post-cyclone nutrient concentrations in the various components of the litter layers Tulasewa, Korokula and Koromani forests. Concentrations in % for macronutrients and in ppm for micronutrients.*

	N	P	K	Ca	Mg	B	Mn	Zn
TULASEWA FOREST (Planted 1984)								
Needles Jan'90-Sep'90								
Pre-cyclone mean (n=7)	0.409	0.019	0.068	0.901	0.212	9.4	610	31
Standard deviation	*0.017*	*0.001*	*0.011*	*0.034*	*0.015*	*0.8*	*67*	*2*
Needles Jan'91-Jul'91								
Post-cyclone mean (n=3)	0.877	0.056	0.141	0.794	0.213	9.2	680	32
Standard deviation	*0.045*	*0.004*	*0.051*	*0.002*	*0.007*	*0.5*	*42*	*0*
Woody parts	0.306	0.036	0.148	0.147	0.088			
Male flowers	0.853	0.060	0.109	0.298	0.227			
Undergrowth Jan'90-Sep'90								
Pre-cyclone mean (n=7)	0.528	0.026	0.112	0.235	0.157			
Standard deviation	*0.003*	*0.001*	*0.006*	*0.037*	*0.011*			
Undergrowth Jan'91-Jul'91								
Post-cyclone mean (n=3)	0.857	0.051	0.131	0.580	0.236			
Standard deviation	*0.106*	*0.008*	*0.038*	*0.125*	*0.029*			
KOROKULA FOREST (Planted 1979)								
Needles Jan'90-Sep'90								
Pre-cyclone mean (n=7)	0.478	0.021	0.049	0.763	0.298	12.5	443	14
Standard deviation	*0.036*	*0.004*	*0.004*	*0.050*	*0.017*	*1.8*	*24*	*2*
Needles Jan'91-Jul'91								
Post-cyclone mean (n=3)	0.783	0.037	0.088	0.731	0.285	11.3	445	21
Standard deviation	*0.085*	*0.002*	*0.011*	*0.017*	*0.035*	*0.4*	*24*	*2*
Branches/twigs	0.240	0.015	0.055	0.203	0.090			
Cones	0.430	0.020	0.077	0.068	0.113			
Male flowers	0.793	0.035	0.057	0.314	0.236			
Undergrowth	0.761	0.036	0.119	0.551	0.294			
KOROMANI FOREST (Planted 1975)								
Needles Jan'90-Sep'90								
Pre-cyclone mean (n=7)	0.434	0.011	0.092	0.709	0.210	10.2	632	16
Standard deviation	*0.050*	*0.003*	*0.018*	*0.038*	*0.016*	*1.2*	*62*	*2*
Needles Jan'91-Jul'91								
Post-cyclone mean (n=3)	0.802	0.046	0.102	0.705	0.215	11.5	764	22
Standard deviation	*0.060*	*0.003*	*0.034*	*0.009*	*0.009*	*1.0*	*33*	*1*
Woody parts	0.379	0.027	0.071	0.244	0.102			
Male flowers	0.817	0.044	0.059	0.345	0.172			
Undergrowth	0.933	0.049	0.083	0.733	0.235			

Table 12.9: *Significance levels for within- and between-site differences in mean nutrient concentrations in pre- and post-cyclone needle litter.*

Difference in means of needle litter	N	P	K	Ca	Mg	B	Mn	Zn
Tulasewa pre- <> post-cyclone	<***	<***	<***	>***	ns	ns	<*	ns
Korokula pre- <> post-cyclone	<***	<***	<***	ns	ns	ns	ns	<***
Koromani pre- <> post-cyclone	<***	<***	ns	ns	ns	<*	<***	<***
Pre-cyclone Tulasewa <> Korokula	<***	ns	>***	>***	<***	<***	>***	>***
Pre-cyclone Tulasewa <> Koromani	ns	>***	<***	>***	ns	ns	ns	>***
Pre-cyclone Korokula <> Koromani	>*	>***	<***	>**	>***	>**	<***	ns
Post-cyclone Tulasewa <> Korokula	ns	>***	ns	>***	<**	<***	>***	>***
Post-cyclone Tulasewa <> Koromani	ns	>**	ns	>***	ns	<**	<**	>***
Post-cyclone Korokula <> Koromani	ns	<***	ns	>*	>**	ns	<***	ns

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

Table 12.10: *Average pre- and post-cyclone nutrient content (kg ha^{-1}) of litter standing crop in the Tulasewa forest plot.*

	N	P	K	Ca	Mg	B	Mn	Zn
Pre-cyclone needle litter	12.0	0.6	2.1	26.8	6.3	0.03	1.8	0.09
Standard deviation	*4.9*	*0.2*	*1.1*	*11.8*	*2.6*	*0.01*	*0.9*	*0.04*
Post-cyclone needle litter	64.7	4.2	10.7	59.0	15.8	0.07	5.0	0.24
Standard deviation	*7.6*	*0.7*	*4.9*	*9.5*	*2.1*	*0.01*	*0.6*	*0.04*
Pre-cyclone woody litter	3.0	0.4	1.5	1.5	0.9			
Standard deviation	*4.9*	*0.6*	*2.4*	*2.4*	*1.4*			
Post-cyclone woody litter	12.4	1.5	6.0	6.0	3.6			
Standard deviation	*1.8*	*0.2*	*0.9*	*0.9*	*0.5*			
Pre-cyclone male flower litter	0.4	0.0	0.1	0.2	0.1			
Standard deviation	*0.4*	*0.0*	*0.0*	*0.1*	*0.1*			
Post-cyclone male flower litter	0.4	0.0	0.1	0.1	0.1			
Standard deviation	*0.3*	*0.0*	*0.0*	*0.1*	*0.1*			
Pre-cyclone undergrowth litter	34.6	1.7	7.4	15.2	10.3			
Standard deviation	*4.7*	*0.2*	*1.2*	*2.2*	*1.7*			
Post-cyclone undergrowth litter	49.3	2.9	7.4	32.5	13.6			
Standard deviation	*6.9*	*0.3*	*1.3*	*1.0*	*1.8*			
Pre-cyclone total	**50.2**	**2.6**	**11.0**	**43.6**	**17.6**			
Post-cyclone total	**126.9**	**8.6**	**24.2**	**97.6**	**33.0**			

Table 12.11: *Average pre-cyclone and post-cyclone nutrient content (kg ha^{-1} of litter standing crop in the Korokula forest plot.*

	N	P	K	Ca	Mg	B	Mn	Zn
Pre-cyclone needle litter	43.3	1.9	4.4	68.6	26.8	0.11	4.0	0.13
Standard deviation	*7.6*	*0.5*	*0.8*	*8.5*	*3.5*	*0.03*	*0.7*	*0.03*
Post-cyclone needle litter	88.5	4.2	10.4	84.0	33.3	0.13	5.1	0.23
Standard deviation	*8.9*	*0.6*	*3.6*	*15.1*	*9.3*	*0.03*	*0.8*	*0.03*
Pre-cyclone branch/twig litter	1.7	0.1	0.4	1.4	0.6			
Standard deviation	*0.9*	*0.1*	*0.2*	*0.7*	*0.3*			
Post-cyclone branch/twig litter	10.0	0.6	2.3	8.5	3.8			
Standard deviation	*2.1*	*0.1*	*0.5*	*1.7*	*0.8*			
Pre-cyclone male flower litter	2.5	0.1	0.2	1.0	0.7			
Standard deviation	*0.7*	*0.0*	*0.0*	*0.3*	*0.2*			
Post-cyclone male flower litter	0.9	0.0	0.1	0.3	0.3			
Standard deviation	*0.5*	*0.0*	*0.0*	*0.2*	*0.2*			
Pre-cyclone cone litter	5.1	0.2	0.9	0.8	1.3			
Standard deviation	*2.1*	*0.1*	*0.4*	*0.3*	*0.5*			
Post-cyclone cone litter	14.4	0.7	2.6	2.3	3.8			
Standard deviation	*4.3*	*0.2*	*0.8*	*0.7*	*1.1*			
Pre-cyclone undergrowth litter	9.6	0.5	1.5	6.9	3.7			
Standard deviation	*5.3*	*0.3*	*0.8*	*3.9*	*2.1*			
Post-cyclone undergrowth litter	14.5	0.7	2.3	10.5	5.6			
Standard deviation	*4.2*	*0.2*	*0.7*	*3.0*	*1.6*			
Pre-cyclone total	**62.1**	**2.8**	**7.4**	**78.7**	**33.2**			
Post-cyclone total	**128.4**	**6.2**	**17.6**	**105.6**	**46.7**			

the pines; Table 12.7) the contributions of macronutrients in undergrowth litter were considerable, ranging between 15–34% for N, 16–44% for P, 19–20% for K, 9–23% for Ca and 11–23% of the total for Mg, with the lower values observed in the Korokula forest plot. The high litterfall resulting from cyclone interference caused a decrease in the proportions of macronutrients in undergrowth litter to 33–41%, 10–13% and 17–26% of the respective totals in the Tulasewa, Korokula and Koromani forest plots (Tables 12.10–12.12).

12.6 Litter Dynamics in *Pinus caribaea* Plantations

Due to the large (and unpredictable) impact of cyclones on litterfall, and because of the effects of differences in soil type and forest stocking on litter fall, accurate predictions for changes in litter production during a rotation period are difficult to make for the Fijian case. However, the pre-cyclone averages obtained during the present study may be used as a first estimate since high litterfall after the passage of a cyclone will be more or less compensated by below average litterfall in the subsequent regeneration phase (*cf.* Table 12.1).

Comparison of pre-cyclone litter production in the Fijian forests with those of forests in Nigeria and Puerto Rico revealed that the variation in litter production for forests of similar age can be considerable (Table 12.13). Annual amounts of litterfall

Table 12.12: *Average pre-cyclone and post-cyclone nutrient content (kg ha^{-1} of litter standing crop in the Koromani forest plot.*

	N	P	K	Ca	Mg	B	Mn	Zn
Pre-cyclone needle litter	36.4	0.9	7.7	59.6	17.6	0.09	5.3	0.13
Standard deviation	*4.5*	*0.2*	*1.3*	*7.0*	*2.3*	*0.01*	*0.5*	*0.01*
Post-cyclone needle litter	86.0	4.9	11.7	76.6	23.2	0.13	8.3	0.24
Standard deviation	*9.3*	*0.6*	*5.9*	*13.7*	*3.4*	*0.03*	*1.6*	*0.04*
Pre-cyclone woody litter	8.4	0.6	1.6	5.4	2.3			
Standard deviation	*4.0*	*0.3*	*0.8*	*2.6*	*1.1*			
Post-cyclone woody litter	27.6	2.0	5.2	17.7	7.4			
Standard deviation	*8.9*	*0.6*	*1.7*	*5.7*	*2.4*			
Pre-cyclone male flower litter	2.0	0.1	0.1	0.9	0.4			
Standard deviation	*0.4*	*0.0*	*0.0*	*0.2*	*0.1*			
Post-cyclone male flower litter	1.2	0.1	0.1	0.5	0.2			
Standard deviation	*0.5*	*0.0*	*0.0*	*0.2*	*0.1*			
Pre-cyclone undergrowth litter	24.4	1.3	2.2	19.2	6.1			
Standard deviation	*9.5*	*0.5*	*0.8*	*7.4*	*2.4*			
Post-cyclone undergrowth litter	39.6	2.1	3.5	31.1	10.0			
Standard deviation	*10.6*	*0.6*	*0.9*	*8.3*	*2.7*			
Pre-cyclone total	**71.2**	**2.9**	**11.6**	**85.1**	**26.5**			
Post-cyclone total	**154.3**	**9.1**	**20.5**	**125.9**	**40.9**			

have been plotted against forest age in Figure 12.6 and show a general increase with age. The production of the Puerto Rican forests was high compared to those of the Fijian and Nigerian forests, which may be related to differences in the rainfall regimes (Figure 12.6). If the impact of cyclones on litterfall is taken into account for the Fijian forests, litter production becomes higher than the values presented for any of the forests in Nigeria or Puerto Rico (Table 12.13). However, because Puerto Rico is also situated in a zone that is occassionally traversed by hurricanes (return period 21 years according to Salivia, 1972), the average annual production of litter over the period of a rotation (including that induced by cyclones) may be somewhat higher than the values presented by Cuevas (1991) and Lugo (1992). Lodge *et al.* (1991) measured pre-hurricane and hurricane litterfall after hurricane Hugo (1989) passed over rain forests in Puerto Rico and obtained results similar to those found in the present study.

An overview of nutrient returns in litterfall for several *Pinus caribaea* plantation forests of varying age in Fiji, Nigeria and Puerto Rico is presented in Table 12.13. Because concentrations of nutrients in litterfall did not vary too much between forests, the return of nutrients to the forest floor via litterfall was strongly related to the annual litterfall amounts. Similar nutrient returns were therefore found for the Nigerian and Fijian forests, whereas a higher return was observed for the 19.5 year old forest in Puerto Rico. However, if nutrients in litterfall during the passage of cyclones are taken into consideration, the returns for the Fijian forests are higher than those of any of the other forests.

The accumulation of litter with increasing forest age in the Fijian study forests has been plotted in Figure 12.9 (both pre- and post-cyclone data), together with those measured in *Pinus caribaea* forests in other tropical countries. The actual amounts

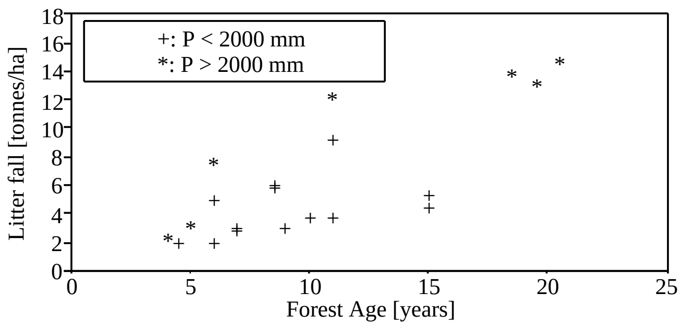


Figure 12.7: *Litterfall in Pinus caribaea forests in Fiji, Nigeria and Puerto Rico, differentiated according to the annual rainfall total (P).*

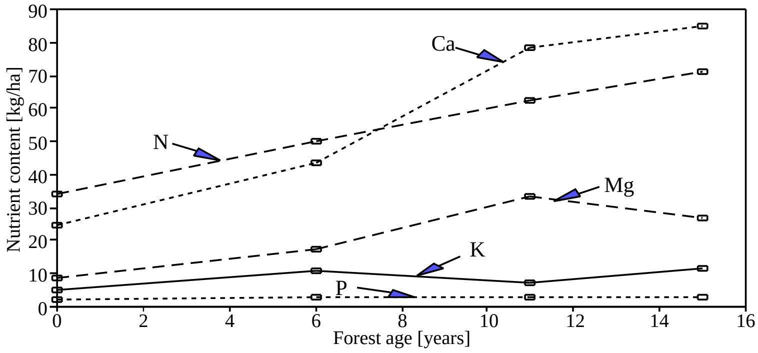


Figure 12.8: *Amounts of macronutrients in the pre-cyclone litter layer* versus *forest age in the study forests.*

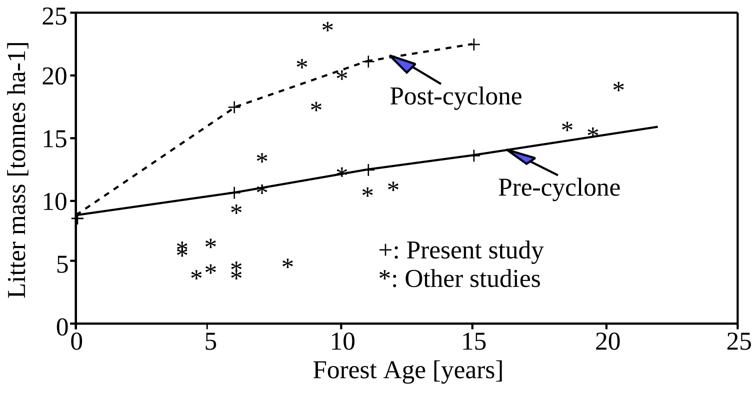


Figure 12.9: *Amounts of litter on the forest floor* versus *forest age for Pinus caribaea plantation forests in various tropical countries. The solid regression line describes the accumulation of litter with forest age in the study sites.*

Table 12.13: *Annual amounts of litterfall (t ha^{-1}) and associated nutrient returns in litterfall (kg ha^{-1}) for Pinus caribaea plantations of varying age in Fiji, Nigeria and Puerto Rico.*

Location	**Alt.** [m]	**P** [mm]	**Dry months**	**Age**	**Litter fall** Total	Needle	**Nutrient returns** N	P	K	Ca	Mg	**Reference**
FIJI												
Cyclone Sina excluded												
Tulasewa	116	1800	6	6	5.0	4.8	19.0	0.8	4.6	43.1	9.7	Present study
Korokula	50			11	9.3	6.7	34.2	1.9	8.9	56.9	24.7	
Koromani	90			15	5.4	4.6	20.6	0.9	5.5	33.1	10.4	
Cyclone Sina included												
Tulasewa	116	1800	6	6	26.5	10.9	92	10	51	102	31	Present study
Korokula	50			11	26.1	15.4	137	9	42	119	59	
Koromani	90			15	23.8	10.8	108	7	37	99	32	
NIGERIA												
Kaduna	610	1250	5	7	3.0							Kadeba(1991)
				9	3.1							
				11	3.7							
				15	4.5							
Afaka	610	1250	5	7	3.1		13.1	0.6	7.3	16.7	5.8	Kadeba & Aduayi {1985)
				10	3.7		16.8	0.7	7.3	19.6	6.8	
Ibadan	230	1330	5	6	2.0							Egunjobi (1975)
Ibadan	230	1330	5	4-5	1.9	1.9	7.3	0.4	6.9	11.4	2.7	Egunjobi & Fasehun (1972)
				7-10	6.0		26.9	0.6	13.6	35.9	10.7	
Ibadan	230	1330	5	7-10	5.8		25.5	0.6	14.5	34.0	10.9	Egunjobi & Onweluzo (1979)
PUERTO RICO												
Luquillo	350	3360	0	11	12.1	9.1						Cuevas et al. (1991)
Luquillo	220	3900	0	4	2.1	2.1						Lugo (1992)
				5	3.1	3.0	14.0	0.7	3.4			
				6	7.4	6.8						
				18.5	13.6	11.9						
				19.5	12.9	11.9	86.0	2.5	9.6			
				20.5	14.5	12.6						

are given in Table 12.15. The data show a general accumulation of litter with forest age, although the scatter is considerable. A regression line was fitted through the grassland and pre-cyclone forest litter standing crop data collected in Fiji to describe the increase in litter layer mass (M_l, kg ha^{-1}) with forest age (A_f, in years):

$$M_l = 8709(\pm 167) + 327(\pm 15) \cdot A_f \qquad \text{n}=4,\ r^2 = 1.00 \tag{12.2}$$

A comparison of litter accumulation in the Nigerian stands with those in Puerto Rico shows that the scatter must be due to differences in decomposition rates rather than litter production rates, because litter production was highest in the Puerto Rican forests (Table 12.13). The high values found for the Brazilian forests may be due to inclusion of decomposing slash from the previous rain forest (Table 12.15).

The accumulation of macronutrients in the litter layer of the Fijian plantations during a rotation period is shown in Figure 12.8. Nutrient contents increased over a rotation period but the accumulation rate was not similar for all nutrients.

The largest relative accumulations were observed for Ca and Mg, with amounts stored in the litter layer at the end of the rotation being 3.5 (Ca) to 3.0 (Mg) times those in the litter layer in the Nabou grassland site. Contents of N and K increased by factors of 2.1 and 2.4, respectively, whereas the accumulation of P was relatively slow as the content increased by a factor of 1.4 only. The Ca and Mg contents of the litter layer in Korokula forest were relatively high, whereas the K content was relatively low. This was attributed to differences in the site quality. In contrast to the other macronutrients, N and P contents showed a linear increase with forest age and the accumulation of these nutrients therefore seemed rather independent of site quality (Figure 12.8). Linear regression analysis was used to obtain expressions ($Y = a \cdot X + b$) describing the change in nutrient content of the litter layer (Y) with forest age (X). The resulting regression constants and coefficients of determination (r^2) are given in Table 12.14. The latter were particularly low for Zn, which showed

Table 12.14: *Regression constants and their standard errors (between brackets) and coefficients of determination for expressions describing the changes in nutrient content (kg ha^{-1}) of the litter layer with forest age (years) in SW Viti Levu. Lines were fitted through four data points representing age 0, 6, 11 and 15 years.*

Nutrient	a	b	r2	Nutrient	a	b	r2
N	2.47(0.07)	34.62 (0.76)	1.00	**Mg**	1.42 (0.57)	10.20 (6.42)	0.75
P	0.05 (0.01)	2.17 (0.11)	0.94	**Mn**	0.21 (0.09)	1.65 (0.98)	0.75
K	0.34 (0.25)	5.97 (2.82)	0.48	**B**	0.0048 (0.0026)	0.0284 (0.0296)	0.62
Ca	4.35 (0.64)	23.22 (7.22)	0.96	**Zn**	0.0004 (0.0022)	0.1180 (0.0252)	0.01

[thb]

little variation with age, and for K, which was exceptionally low at Korokula forest. The mean annual increase in the nutrient content of the litter layer over a rotation is given by the regression constant a, whereas b approximates the nutrient content of the litter layer in the preceding grassland.

Table 12.15 illustrates the large variation exist between the amounts of nutrients that may be immobilized in the litter layers of *Pinus caribaea* forests of similar age. For instance, the N content of the litter layer in 9–11 year old forests ranged from 62 to 160 kg ha^{-1} with an average of 91 kg ha^{-1}. Similar differences were observed for the other nutrients. Some of these variations may be explained by differences in density and composition of the undergrowth.

Table 12.15: *Amounts of litter (t ha^{-1}) and nutrient content of litter (kg ha^{-1}) for Pinus caribaea plantations in the tropics.*

Location	Alt. [m]	P [mm]	Dry months	Age	Total	Needle	N	P	K	Ca	Mg	Reference
					Litter on the forest floor							
FIJI												
Tulasewa	116	1800	6	6	10.6	3.0	50	2.6	11.0	44	17.6	Present study
Korokula	50	1800	6	11	12.5	9.0	62	2.8	7.4	79	33.2	Present study
Koromani	90	1800	6	15	13.5	8.4	71	2.9	11.6	85	26.5	Present study
BRAZIL												
Jari Florestal	50	2300	5	6	64.7		227	12.9	12.9	175	84.1	Chijioke (1980)*
Jari Florestal	50	2300	5	9.5	23.8		160	4.8	11.9	76	21.5	Russell (1983)
NIGERIA												
Afaka	610	1250	5	7	10.6		53.1	2.1	14.9	67	17	Kadeba & Aduayi {1985)
				10	12.1		66.7	2.4	15.8	83	20.6	
Ibadan	230	1330	5	6	3.7		18.1	0.4	8.9	7	3.6	Egunjobi & Bada (1979)
				8	4.6							
				9	17.3							
				10	19.7		88.7	2	47.3	39.4	13.8	
Ibadan	230	1330	5	4-5	3.7		13.3	0.7	10	24.1	5.2	Egunjobi & Fasehun (1972)
Ibadan	230	1330	5	7-10	20.7							Egunjobi & Onweluzo (1979)
AUSTRALIA												
Beerburrum, A	20		5	5	4.2							Richards & Bevege (1967)
TRINIDAD												
Matura		2800	0	4	6.1		39	2.0	7.0	51	10.0	Cornforth (1970)
Valencia	70	3300	0	6	4.4		30	1.0	4.0	39	7.0	
Melajo	200	3000	0	7	13.1		90	4.0	5.0	123	29.0	
Cumuto	10	2500	0	4-12	11.0		77	8.0	12.0	94	16.0	
PUERTO RICO												
Luquillo	350	3360	0	11	10.5	6.1						Cuevas et al. (1991)
Luquillo	220	3900	0	4	5.6	5.2						Lugo (1992)
				5	6.2	5.7	37	1.8	6.5			
				6	9.1	7.8						
				18.5	15.7	12.6						
				19.5	15.2	12.3	102	3.8	9.8			
				20.5	18.9	13.8						

*: includes undergrowth

Chapter 13

Nutrient Fluxes in Water

13.1 Introduction

Water is the medium in which considerable amounts of non-gaseous elements are transferred between the various compartments of an ecosystem (*e.g.* atmosphere, vegetation, soil). The amounts of rainfall, throughfall, litter percolate and drainage were quantified for each of the forest plots in Chapter 6, whereas the cycling of nutrients via litterfall was discussed in the previous chapter. To complete the picture, changes in the chemical composition of rain water as it passes through the forest ecosystem and associated nutrient fluxes between the various system compartments will be discussed in this chapter.

13.2 Field and Laboratory Procedures

13.2.1 Sampling of Soil Moisture

The sampling procedures for rain water, throughfall, stemflow and litter percolate have already been discussed in Section 6.2. Vacuum tube lysimeters (Wood, 1973) were used to sample soil moisture for the determination of its chemical composition. The lysimeters were pre-treated by leaching with a 0.1 N HCl solution and rinsing with distilled water (EC= 2 μS cm^{-1}) until the electrical conductivity (EC) of the extracted solution was similar to that of the distilled water. The samplers were installed with their ceramic cups just below the A-horizon at depths of 20–30 cm, or well within the B/C- horizon at depths of 60–90 cm. The dates of installation and removal of the lysimeters, the number of lysimeters in each plot, and the depths of the cups are given in Table 13.1. A vacuum of about 500 mbar was obtained with a hand vacuum pump. The determination of the quality of soil moisture is difficult as there are sources of error (Haines *et al.*, 1982) associated with the method used to extract the moisture, as well as with spatial variation. The chemical composition of moisture collected with suction lysimeters is known to vary with the suction that is applied, with moisture being extracted from increasingly smaller pores with increasing suction (Nortcliff and Thornes, 1989). In addition, the volume of soil from which the moisture is extracted is unknown. If the applied suction exceeds that prevailing in the soil, H_2CO_3 may leave the soil solution in gaseous form, thereby changing its pH and HCO_3^- concentration.

Table 13.1: *Depths, installation dates and removal dates of vacuum tube lysimeters in the Tulasewa, Korokula and Koromani forest plots.*

Plot	Code	Number	Depth	Start	End	Remarks
Tulasewa	PU 20-2	2,4,6,8	30- 35 cm	Dec/Jan 1989	Sep 1991	A/B horizon, clay-loam
Forest		1,3,5,7	90-110 cm	Dec/Jan 1989	Sep 1991	C horizon, RR, sandy loam
Korokula	PU 09-5	2,4,6	19- 25 cm	Jan 1990	Sep 1991	A-horizon, fine sand
Forest		1,3,5	37- 95 cm	Jan 1990	Sep 1991	At bedrock, gravelly sandy loam
Koromani	PU 09-4	2,4	25- 30 cm	Dec 1989	Sep 1991	B horizon, sandy loam
Forest		1,3	100 cm	Dec 1989	Sep 1991	C horizon, RR, sandy loam
		6,8	25- 30 cm	Jul 1990	Sep 1991	B horizon, sandy loam
		5,7	80- 85 cm	Jul 1990	Sep 1991	C horizon, clay loam

Furthermore, the ceramic material of the cup may selectively absorb some of the ions from the solution passing through its pores (particularly P, NO_3, NH_4), and release other ions (notably Na, Mg, Si, SO_4; Hansen and Harris, 1975; Zimmermann *et al.*, 1978). To minimize such influences on the composition of soil moisture samples, water extracted on the first two occasions after installation was not sampled. The first sample was therefore usually not collected within two weeks after the installation of the lysimeter. The lysimeters were emptied at least once a week during the wet season when the soil was sufficiently moist, but less regular during the dry season. The moisture was collected in 250 ml plastic measuring cylinders. Samples collected at corresponding depths were bulked for each plot and stored in the dark until sufficient water had been collected for analysis.

13.2.2 Sampling and Analytical Procedures

The EC of rainfall, throughfall, litter percolate and soil moisture were measured in the field on each sampling occasion with an EC-meter developed at the electronics department of FES-VUA. The EC-values (μS cm^{-1}) were automatically normalized to a temperature of 25 °C. The accuracy was 2 μS cm^{-1} for the most frequently used range of 0–100 μS cm^{-1} and 4 μS cm^{-1} for the range 0–200 μS cm^{-1}. Separate readings were made for each gauge unless the collected amounts were not sufficient. In such cases measurements were made after bulking of individual samples.

Rain water samples for chemical analysis were taken at monthly intervals during dry periods and more frequently during wet periods from water collected by the special raingauge, as described in Section 6.2. The samples were collected shortly after large storms ($P > 30$ mm) to include both wet and dry deposition of the preceding period. The weekly or bi-weekly bulk samples of throughfall, litter percolate and soil moisture were stored in the dark until sampling occurred. Throughfall and litter percolate samples were always collected on the same day as rain water samples. Soil moisture samples were taken less frequently, normally after enough moisture had been extracted (about 1.5 l).

In addition, two seawater samples were collected in December 1990 and July 1991 at Natadola Harbour to enable the determination of the contribution of maritime components to the chemical composition of rainfall. The EC of seawater was measured after dilution with pure rain water (EC= 2 μS cm^{-1}) by a factor 20 to remain within the range of 0–5000 μS cm^{-1}.

To obtain estimates of the nutrient output in streamflow from the forested Oleolega catchment, 21 samples were collected under baseflow conditions. Due to time and manpower constraints, the remoteness of the site which could be reached by car during periods with high rainfall only with great difficulty, and the high spatial variation of rainfall in the Nabou area, only 27 stormflow samples could be collected despite numerous attempts. To overcome this problem to some extent, the EC (a measure of the total ion concentration in the solution) and temperature of the streamflow were measured at 20 minute intervals with an EC datalogger system developed at the FES-VUA from April 19, 1990, onwards. The EC measurements by the datalogger system had to be corrected for temperature variations and were normalized to a temperature of 25 °C. Linear regression equations were used to calibrate the EC datalogger system against the manually operated EC meters (Schellekens, 1992; Assenberg, 1993). Although no diurnal variation was observed in the EC readings of streamflow as read with the manually operated EC meters, the datalogger system suggested such a variation even after temperature correction. Furthermore, unexplained variations occurred occasionally due to malfunctioning of the datalogger system, which also showed a lack of sensitivity when the instrument was not properly adjusted (Schellekens, 1992; Assenberg, 1993).

Pre-cyclone baseflow samples were collected at the usual sampling site in the Oleolega catchment (Figure 3.4), at a location further downstream near the junction of Oleolega Creek and the Kubuna River (Planning Unit 10-5), and in the adjacent Naruku catchment (Planning Unit 10-3) (see also Figure 2.2) to give an impression of the spatial variability of baseflow composition for forested catchments of varying size in the area. Samples representing baseflow from a nearby grassland catchment were collected from the Ividamu creek (Planning Unit 10-1, 10-6; see Figure 2.2) upstream from the junction with the Kubuna River. This catchment drains the area SW of the Naruku Catchment and the geology of the area was thought to be similar to that of the Naruku catchment, where the parent rock consisted of Kalaka dacite. Samples were collected on the same day on five occasions between August 1990 and December 1990. However, only 3 samples could be collected from the Naruku catchment because the creek fell dry at the end of the dry season. Another 10 samples were collected at each site during the post-cyclone period.

Water samples for cation analysis, Si and PO_4 were collected in 100 ml polyethylene bottles after filtering through a 0.45 μm Millipore filter. Each bottle had been rinsed with a 10% HNO_3 solution to remove any adsorbed ions before rinsing six times with distilled water (EC= 2 μS cm^{-2}). For conservation purposes 0.7 ml of 65% HNO_3 suprapur was added to the bottle prior to the sampling, resulting in a final sample pH of about 1. Streamflow samples for cation analysis were collected with a syringe from the center of the creek some 15 m upstream from the culvert to avoid any contamination of the samples by Ca and HCO_3 from the cement of the culvert.

Water samples for anion analysis, total N, total P and laboratory measurements of EC and pH were collected in 200 ml polyethylene bottles. These bottles had been rinsed 6 times with distilled water and another six times with the sampling solution prior to sampling. To avoid any contamination with NO_3 the 200 ml sample was always collected before the acidified sample. Streamflow samples for anion analysis were collected in the center of the Oleolega creek after the bottles had been rinsed 6 times with streamwater collected at a spot downstream from where the sample would be collected. The bottles were closed below the waterlevel to avoid air bubbles in the sample and the acidified sample was collected at the same spot immediately afterwards. All samples were stored in a refrigerator at about 4 °C before shipment to the Netherlands by airfreight for analysis at FES-VUA.

The EC, pH and the presence of NO_3/NO_2 were determined in the field during sampling. The pH was measured with a combined electrode (INGOLD, type U402-S7/120) connected to a pH-meter (Metrohm AG., Model E-604). The electrode was calibrated before each measurement using two buffer solutions (Baker Chemical Co.) with pHs of 4.00 and 7.00 at 25 °C, respectively. The error in the pH measurements was typically less than 0.1 pH unit. An estimate of the nitrate concentration of the samples was obtained using non-bleeding nitrate test strips (Merckoquant 10020, Merck).

Separate water samples were collected for the determination of alkalinity (HCO_3) and hardness (Ca+Mg). These were determined in a field laboratory in Nadi, usually within 24 hours after the sampling. Alkalinity was measured by titration (HACH Digital Titrator) of the solution with 0.4 N H_2SO_4 after adding an indicator consisting of a mixture of Br-Cresolgreen (150 mg), methylred (100 mg) and 96% ethanol (200 ml). Hardness was determined by titration of the solution with Na-EDTA after adding an indicator (Merck, No. 11122).

13.2.3 Laboratory Procedures

The EC and pH were remeasured in the laboratory at FES-VUA with a Phillips digital conductivity meter (Model PW-9526) and a digital pH-meter (Orion Research, Model 701A) connected to a combined electrode (Orion Research), respectively. The pH-meter was calibrated against buffer solutions (Baker Chemical Co.) with pHs of 4.00 and 7.00 at 25°C.

Concentrations of Na and K were determined by flame photometry using an Eppendorf flame photometer. Concentrations of Al, Ca, total Fe, Mg, Mn and Si were determined on a Perkin-Elmer (Model 6500) Inductively Coupled Plasma (ICP) emission spectrophotometer. Concentrations of Cl, SO_4, NO_3, PO_4 and NH_4 were determined by spectrophotometry on Technicon and Skalar Auto-analyzers according to the following automated methods. Chloride was determined with the ferricyanide method of Zall *et al.* (1956), SO_4 was determined with the methylthymol-blue method of Greenberg *et al.* (1980), NO_3 by cadmium reduction (Hendrikson and Selmer-Olsen, 1970), PO_4 by ascorbic acid reduction (Black *et al.* 1965) and NH_4 with the modified Berthelot reaction using salicylate and dichloroisocyanurate (Krom, 1980). Total P was determined on the ICP after destruction using the molybdiphosphoric acid method of Boltz and Mellon (1948). Total N was determined as NH_4 on the ICP after destruction (Kjeldahl digest). HCO_3 was not remeasured.

The analytical accuracy was assumed to be within 2% of the concentrations in the highest standard solutions and the maximum errors for each constituent are given in Table 13.2.

13.3 Chemical Composition of Rainfall and Atmospheric Inputs

The atmospheric input of chemical constituents to a forested ecosystem is governed by two processes, wet and dry deposition (Whitehead and Feth, 1964). The deposited solids during intermediate dry periods may dissolve rapidly during periods with rain-

Table 13.2: *Maximum absolute analytical errors in concentrations (mg l^{-1}) of constituents in water samples as determined st FES-VUA (Mrs. T. Bäer, pers. comm.).*

Species	Error	Species	Error	Species	Error	Species	Error
Na	0.40	NH_4^+	0.03	Cl^-	0.40	Fe-Total	0.04
K	0.10	Al^{3+}	0.04	SO_4^{2-}	0.60	N-Total	0.02
Ca	0.24	Mn^{2+}	0.04	NO_3^-	0.20	P-Total	0.02
Mg	0.20	Si^{4+}	0.40	PO_4^{3-}	0.02		

fall. During the present study bulk samples of rainfall were collected shortly after large storms. In this way composite samples of dry deposition, as intercepted by the rainfall gauges during preceding dry periods, and wet deposition during the rainfall events were obtained. There are several problems associated with the measurement and calculation of atmospheric inputs to an ecosystem (Waring and Schlesinger, 1985; Bruijnzeel, 1991), some of which are listed below. Ion concentrations in rain water are generally low which can lead to large analytical errors if the sensitivity of the analysis is not sufficient. Because the trapping surface area for dry deposition of a raingauge is smaller than that of forests, and because forests are better exposed to winds, the dry deposition component may be underestimated by a rain gauge. To complicate the matter further, some of the dry deposition may be produced by the ecosystem under consideration (*e.g.* pollen; gaseous emissions) and therefore does not constitute a real input to the system (Stoorvogel, 1993).

The chemical composition of rain water collected by a rain gauge depends on the source of water (*e.g.* maritime or terrestrial), on constituents (*e.g.* aerosols, gaseous emissions by industry or volcanoes) picked up during transport through the atmosphere and on the composition of the dry deposition (Appelo and Postma, 1993). Particles of salt may be considered the main source of ions for both wet and dry deposition. In the atmosphere above the oceans such salt particles form during the breaking of waves when fine droplets of seawater are ejected into the atmosphere. After evaporation of the water, solid salt particles are formed which can be transported upwards by winds and may act as condensation nuclei for the generation of raindrops in clouds (Drever, 1982). Fractionation during the forming of these salt particles does not play an important role for the major ions (Na, K, Ca, Mg, Cl, SO_4) (Duce and Hoffman, 1976). Therefore these ions are present in precipitation in the same proportions as they were in seawater and rainfall on small oceanic islands may therefore be considered as very dilute seawater.

On larger islands or continents the composition of rain water may be influenced by dust, smoke from burning vegetation or natural and industrial emissions (Appelo and Postma, 1993). The source of ions in rain water may be evaluated by subtraction of the oceanic contribution from the total ion content for each constituent. So-called excess concentrations are then assumed to originate from continental sources (Eriksson, 1960). Chloride ions are only marginally added to rain water by terrestrial sources (at least in non-volcanic and non-industrial areas) and the Cl concentration may therefore be taken to reflect the oceanic contribution. If fractionation during the forming of salts can be neglected, expected oceanic contributions of other ions ($[X_{expected}]$) may be calculated using their proportions with respect to the Cl concentration in seawater

($[Cl_{sea}]$) as shown in Equation 13.1 (Eriksson, 1960).

$$[X_{expected}] = \frac{[X_{sea}]}{[Cl_{sea}]} \cdot [Cl_{rain}] \tag{13.1}$$

The average EC, pH and chemical composition of locally sampled seawater are shown in Table 13.3. The contribution of cations to the total dissolved solids (TDS) in seawater decreased in the order Na > Mg > Ca > K > NH_4 > Si, whereas that of anions decreased in the order Cl > SO_4 > HCO_3 > PO_4 > NO_3. Levels of NO_3, Al, Fe and Mn were below the detection limits.

Weighted averages of EC and pH, as measured in the field during sampling (shown in Table 13.3) with those measured in the laboratory of the FES-VUA (not shown), differed by less than 3 μS cm^{-1} and less than 0.1 pH unit respectively, which is within the range of the instrumental errors, suggesting that no major changes had occurred between sampling and analysis.

Throughout this chapter the 'pre-cyclone period' will represent the period between January 1 and November 23, 1990, the 'cyclone period' the period between November 24 and December 3, 1990, and the 'post-cyclone period' that between December 4, 1990 and September 30, 1991. Weighted average ion concentrations in pre- and post-cyclone rainfall, as well as those in cyclone rainfall (single samples) are presented in Table 13.3. If concentrations fell below the detection limit, the latter was used to calculate the weighted averages, leading to an unavoidable overestimation of the concentration. The concentrations of K, Ca, Mg, SO_4, NO_3, Si, Al, Mn, total Fe and total P in rainfall were often below the detection limits, whereas those of the other ions were just above the detection limits and large analytical errors are therefore to be expected (*cf.* Table 13.2). However, measured concentrations of most ions were consistent throughout the data set and the sensitivity of the analysis was therefore considered sufficient. This suggested that the analytical errors were in fact lower than given in Table 13.2. Some uncertainty existed with respect to the field analysis of HCO_3 in rain water collected at Tulasewa and Oleolega forests because concentrations were usually close to zero, but extremes of 18.3 mg l^{-1} and 24.4 mg l^{-1} were also observed without corresponding increases in EC. Concentrations of HCO_3 at the Korokula and Koromani forest plots remained below 6.7 and 3.7 mg l^{-1}, respectively. This suggested that some contamination may have occurred at the Tulasewa and Oleolega sites and the weighted averages of the HCO_3 concentration given in Table 13.3 for the pre-cyclone period may therefore be seriously overestimated[1].

The concentrations of all constituents in pre- and post-cyclone rain water were extremely low, with weighted averages of EC ranging from 6–7 μS cm^{-1} for the inland rainfall stations at Oleolega and Tulasewa, to 8–9 μS cm^{-1} for the more coastal stations at the Korokula and Koromani sites (See Figure 2.2). Therefore the EC showed a (very weak) negative trend with distance from the ocean. This may be ascribed to lower concentrations of Na and Cl in rain water collected at inland stations, possibly also as a result of dilution due to the increase of rainfall amounts with distance to the coast (*cf.* Weijers and Vugts, 1990; Stuijfzand, 1993).

The chemical composition of rain water collected at any location may vary considerably with time and depends on the amount of rainfall (dilution effect, washing out of aerosols), the length of the preceding dry period (accumulation of dry deposition) as

[1]When contaminated samples were excluded average pre- and post-cyclone concentrations were 1.08 and 0.87 mg l^{-1} at Tulasewa forest, and 1.27 and 1.05 mg l^{-1} at the Oleolega catchment, respectively.

Table 13.3: *Weighted pre- and post-cyclone averages of EC ($\mu S\ cm^{-1}$), pH, and ion concentrations ($mg\ l^{-1}$) in rain water with analytical detection limits ($mg\ l^{-1}$), corresponding concentrations in seawater and derived oceanic contributions for each constituent added for comparison. Analyses of rain water collected after the passage of cyclone Sina represent single samples.*

Location	**EC**	**pH**	**Na**	**K**	**Mg**	**Ca**	**NH4**	**Cl**	**HCO3**	**SO4**	**NO3**	**PO4**	**Si**	**Al**	**Fe-T**	**Mn**	**N-T**	**P-T**
Detection limit			*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.00*	*0.30*	*0.05*	*0.02*	*0.05*	*0.05*	*0.02*	*0.02*	*0.02*	*0.02*
Seawater																		
Natadola	60850	8.34	10820	408	1356	392	0.26	20210	140	2754	0.05	0.39	0.10	0.05	0.02	0.02	0.11	0.03
Bulk precipitation, excluding cyclone events																		
Tulasewa	6	5.62	0.61	0.28	0.06	0.09	0.27	1.20	3.27	0.56	0.15	0.02	0.05	0.05	0.02	0.02	0.16	0.02
Korokula	8	5.50	0.80	0.13	0.06	0.09	0.34	1.52	1.02	0.73	0.24	0.02	0.05	0.05	0.02	0.02	0.56	0.02
Koromani	9	5.49	0.87	0.12	0.06	0.08	0.22	1.61	0.97	0.80	0.11	0.02	0.07	0.03	0.03	0.02	0.32	0.02
Oleolega	7	5.67	0.61	0.15	0.07	0.10	0.28	1.23	5.83	0.87	0.18	0.03	0.09	0.06	0.05	0.03	0.15	0.03
Pre-cyclone bulk precipitation																		
Tulasewa	8	5.57	0.66	0.32	0.06	0.12	0.27	1.33	5.71	0.57	0.17	0.02	0.05	0.05	0.02	0.02	0.13	0.02
Korokula	8	5.42	0.85	0.11	0.07	0.09	0.25	1.55	1.18	0.68	0.10	0.02	0.05	0.05	0.02	0.02	0.34	0.02
Koromani	9	5.50	0.99	0.10	0.07	0.09	0.15	1.62	1.00	0.63	0.09	0.02	0.08	0.03	0.03	0.02	0.22	0.02
Oleolega	7	5.85	0.63	0.12	0.07	0.11	0.23	1.18	9.84	0.70	0.14	0.09	0.10	0.07	0.07	0.05	0.12	0.03
Cyclone precipitation																		
Tulasewa										Not available								
Korokula	100	5.19	15.95	0.65	2.02	0.67	0.12	29.16	0.61	4.57	0.06	0.01	0.05	0.05	0.02	0.02	0.13	0.02
Koromani	120	5.43	19.45	1.17	2.44	0.81	0.13	35.74	0.00	5.83	0.09	0.01	0.05	0.02	0.02	0.02	0.12	0.02
Oleolega	76	4.95	12.10	0.65	1.51	0.54	0.19	21.83	0.00	3.07	0.20	0.01	0.10	0.02	0.02	0.02	0.21	0.02
Post-cyclone bulk precipitation																		
Tulasewa	5	5.67	0.56	0.24	0.06	0.06	0.26	1.08	0.88	0.54	0.13	0.02	0.05	0.06	0.03	0.02	0.17	0.02
Korokula	8	5.64	0.70	0.15	0.06	0.09	0.48	1.46	0.75	0.81	0.46	0.02	0.05	0.05	0.02	0.02	0.67	0.02
Koromani	8	5.47	0.71	0.14	0.05	0.07	0.32	1.59	0.93	1.04	0.14	0.02	0.05	0.03	0.02	0.02	0.37	0.02
Oleolega	8	5.45	0.58	0.18	0.06	0.08	0.34	1.24	1.05	1.11	0.16	0.03	0.09	0.06	0.02	0.02	0.16	0.03
Marine component of bulk precipitation excluding cyclones [%]																		
Tulasewa			106	9	136	25	0	100	0	29	0	0	0	0	0	0	0	0
Korokula			102	24	162	33	0	100	1	28	0	0	0	0	0	0	0	0
Koromani			98	28	172	39	0	100	1	28	0	0	0	0	0	0	0	0
Oleolega			107	17	119	24	0	100	0	19	0	0	0	0	0	0	0	0
Marine component of cyclone precipitation [%]																		
Tulasewa										Not available								
Korokula			98	91	97	84	0	100	33	87	0	6	0	0	0	0	0	0
Koromani			98	62	98	86	0	100	>33	83	0	14	0	0	0	0	0	0
Oleolega			97	68	97	78	0	100	>33	97	0	3	0	0	0	0	0	0

Fe-T: Total Fe; N-T: Total N; P-T: Total P

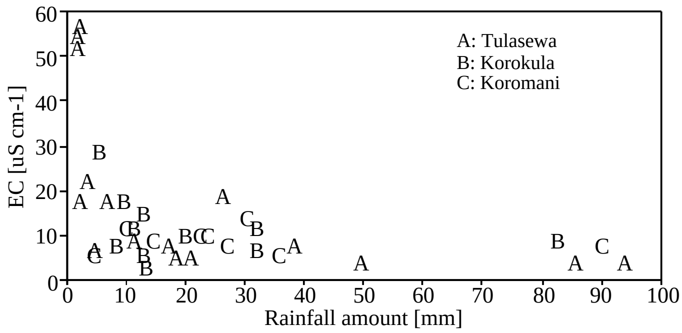


Figure 13.1: *EC-values in rain water from single storm events near the Tulasewa, Korokula and Koromani forest plots against corresponding storm sizes.*

well as on wind speed (cyclones). The EC of rain water collected during periods without cyclones decreased with the storm size as shown in Figure 13.1. EC-values greater than 10 μS cm^{-1} were not observed when rainfall exceeded 35–40 mm. EC-values of rainfall, collected in clean containers (no dry deposition) during large storms in Nadi ranged between 2 to 3 μS cm^{-1}. Such low EC-values in rainfall were also observed by Malmer (1993) in a catchment study in Sabah, Malaysia.

At the height of cyclone Sina large amounts of sea spray were carried inland. This resulted in major increases in the concentrations of Na, K, Mg, Ca, Cl and SO_4 in rain water collected after the cyclone event, as shown in Table 13.3. The highest concentrations were found at Korokula forest which was located at a distance of less than 2 km from the coast. Here the EC of rain water increased from a weighted average of 8 μS cm^{-1} for periods without cyclones to 120 μS cm^{-1} after the event. The deposition of sea spray during the event decreased with the distance from the coast and EC-values of 100 μS cm^{-1} and 76 μS cm^{-1} were observed for rain water collected at the Koromani and Oleolega sites, respectively. Because the funnel of the gauge at the Tulasewa forest site was blown away during the cyclone no samples could be collected. However, EC measurements of throughfall after the cyclone (Section 13.4) suggested that the EC of rain water at Tulasewa must have been considerably lower than those measured at Korokula or Koromani. No such increases in concentrations were observed for rainfall associated with the passage of cyclone Rae in March, 1990, during which wind speeds in SW Viti Levu were much lower than those observed during cyclone Sina (Section 2.4.4).

The oceanic contributions of ions in rain water, expressed as a percentage of the total, are shown Table 13.3 as well. Calculation of excess concentrations for pre- and post-cyclone rain water showed that Na and Mg originated from maritime sources exclusively. Measured Mg concentrations were lower than expected, especially at the coastal stations for which values up to 172% were calculated. However, concentrations of Mg were close to the detection limit, and the adjustment in concentration necessary to obtain a 100% maritime origin was within the range of the maximum analytical error given in Table 13.2. As such it can be safely assumed that all Mg in rainfall was derived from oceanic sources. Ca, SO_4 and K originated partly from maritime and partly from terrestrial sources, whereas the other constituents originated from terrestrial sources exclusively. The contribution of cations to the TDS decreased in the following order Na > NH_4 > K > Mg > Ca > Si. Therefore the addition of NH_4 and K from terrestrial sources in rain water changed the cationic sequence as compared to that in seawater. Dust particles form the main terrestrial source of Si ions and a good correlation with concentrations of K or Ca should be observed if these had been derived from the dissolution of such particles. However, Assenberg (1993) observed no correlation between Si and K or Ca in rain water collected in the Oleolega catchment and suggested that biological sources may have provided the excess concentrations of these constituents. The importance of NH_4 in the cationic sequence also points to a biological source.

As a result of the large contributions of sea spray in cyclone rain water the maritime contributions of Ca, K, SO_4, HCO_3 and PO_4 increased considerably compared to those in pre- and post-cyclone rainfall. similarly, the relative importance of the cations decreased in the order Na > Mg > K > Ca > NH_4 > Si resembling more that observed in seawater.

Atmospheric inputs of nutrients during the study period were calculated by multiplying the ionic concentrations in rain water with the corresponding rainfall totals. Separate estimates were obtained for inputs during the pre- and post-cyclone periods as well as for inputs by cyclone Sina. The results are shown in Table 13.4. As indicated earlier, if the concentration of a constituent dropped below the detection limit, the latter was used in the calculations and actual inputs could therefore be (much) lower than the values presented in Table 13.4. Annual inputs for most constituents, except Na, Cl, SO_4 and HCO_3 were very low compared to many other tropical locations as reviewed by Bruijnzeel (1989a, 1991). In fact, inputs were as low as those observed by Parker (1985) above natural rain forest in Costa Rica. Ionic concentrations in pre- and post-cyclone rain water were fairly similar and differences in corresponding atmospheric inputs were mainly due to differences in rainfall totals. The large inputs of HCO_3 for the pre-cyclone period in Tulasewa and Oleolega were attributed to contamination of some of the samples and the post-cyclone values were therefore thought to be more realistic. Atmospheric nutrient inputs varied relatively little between sites and estimates for the average inputs at Nabou station for years with and without cyclones were made by combining the average annual rainfall for Nabou (Section 6.3) and respective mean weighted average concentrations of the bulk precipitation for all sites. Post-cyclone data only were used for the calculation of annual atmospheric inputs of HCO_3.

As shown in Table 13.4 inputs of Na, Cl and Mg by cyclone Sina exceeded the estimated annual inputs for years without cyclones by two to three times, whereas cyclone inputs of K, Ca and SO_4 were equal to or slightly lower than the corresponding annual inputs. Inputs of constituents supplied by terrestrial sources during cyclone Sina were low compared to their annual inputs, although the latter could have been seriously overestimated. The present data show that cyclones may contribute significant amounts of nutrients (*e.g.* K, Mg) to the ecosystem. Therefore, estimates of the annual atmospheric inputs of nutrients for years with major cyclone events were also calculated (Table 13.4).

Table 13.4: *Rainfall totals (mm) and associated atmospheric inputs of nutrients (solutes, in kg ha^{-1}) for pre- and post-cyclone periods, as well as during cyclone Sina at the four research forests. derived estimates for mean annual atmospheric inputs with standard deviations (SD) at Nabou station for years with and without cyclones added for comparison.*

Location	Rain	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Pre-cyclone atmospheric input																	
Tulasewa	1710	11.3	<5.5	<1.0	<2.1	<4.5	22.8	97.9	<9.8	<2.9	<0.4	<0.9	<0.8	<0.3	<0.3	2.2	<0.4
Korokula	1497	12.8	<1.7	<1.0	<1.3	3.7	23.2	17.6	<10.1	<1.5	<0.3	<0.7	<0.8	<0.3	<0.3	5.1	<0.3
Koromani	1661	16.5	<1.6	<1.1	<1.4	2.5	27.0	16.6	<10.4	<1.5	<0.3	<1.3	<0.5	<0.4	<0.3	3.7	<0.4
Oleolega	1545	9.7	<1.8	<1.1	<1.7	<3.6	18.2	152.0	<10.7	<2.1	<1.4	<1.5	<1.0	<1.2	<0.7	1.9	<0.4
Cyclone input																	
Tulasewa	238								Not available								
Korokula	179	28.6	1.2	3.6	1.2	0.2	52.2	1.1	8.2	0.1	<0.0	<0.1	0.1	<0.0	<0.0	0.2	<0.0
Koromani	195	37.9	2.3	4.7	1.6	0.2	69.7	0.0	11.4	0.2	<0.0	<0.1	<0.0	<0.0	<0.0	0.2	<0.0
Oleolega	239	28.9	1.6	3.6	1.3	0.5	52.1	0.0	7.3	0.5	0.0	<0.2	<0.0	<0.0	<0.0	0.5	<0.0
Post-cyclone atmospheric input																	
Tulasewa	1706	9.5	<4.2	<1.0	<1.0	4.4	18.4	15.0	<9.3	<2.2	<0.4	<0.9	<1.0	<0.4	<0.3	2.9	<0.4
Korokula	1128	7.9	<1.7	<0.6	1.0	5.5	16.5	8.4	<9.2	5.2	<0.3	<0.6	<0.6	<0.3	<0.2	7.5	<0.2
Koromani	1150	8.1	<1.6	<0.6	<0.8	3.7	18.2	10.7	<11.9	1.6	<0.3	<0.6	<0.3	<0.3	<0.2	4.2	<0.2
Oleolega	1241	7.3	<2.2	<0.7	<1.0	4.2	15.4	13.0	<13.8	<2.0	<0.4	<1.1	<0.8	<0.2	<0.2	<2.0	<0.4
Annual atmospheric input for years without cyclones																	
Average	1695	12.3	<2.9	<1.1	<1.5	<4.7	23.5	15.3	<12.5	<2.9	<0.4	<1.1	<0.8	<0.5	<0.4	<5.1	<0.4
SD	*408*	*2.9*	*0.7*	*0.3*	*0.4*	*1.1*	*5.7*	*3.7*	*3.0*	*0.7*	*0.1*	*0.3*	*0.2*	*0.1*	*0.1*	*1.2*	*0.1*
Annual atmospheric input for years with cyclones																	
Average	1695	42.5	<4.2	<4.9	<2.7	<4.4	78.6	13.7	<19.9	<2.9	<0.4	<1.1	<0.8	<0.5	<0.4	<4.7	<0.4
SD	*408*	*10.2*	*1.0*	*1.2*	*0.6*	*1.1*	*18.9*	*3.3*	*4.8*	*0.7*	*0.1*	*0.3*	*0.2*	*0.1*	*0.1*	*1.1*	*0.1*

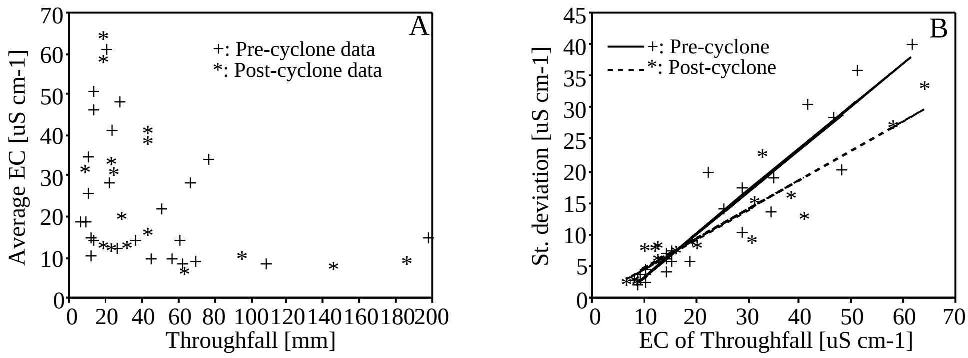


Figure 13.2: *Throughfall amounts against corresponding EC values (A) and the EC of throughfall against corresponding standard deviations (B) for pre- and post-cyclone data collected in the Korokula forest plot.*

13.4 Chemical Composition of Throughfall

Ion concentrations in rain drops hitting the forest canopy generally increase due to the dissolution of dry deposition previously intercepted by the canopy. Subsequent evaporation from the wet canopy (Section 6.4) causes an additional increase proportional to the amount of water evaporated. Furthermore, leaching of nutrients from the foliage and branches occurs and this leads to increases in the concentrations of relatively mobile ions (particularly K), and to a lesser extent of ions immobilised in structural tissue (*e.g.* Ca) (Parker, 1983). Ion concentrations in rain drops falling through the canopy without striking it (free throughfall) do not change and the concentrations in the bulk throughfall measured at the forest floor therefore depend on the collected proportions of crowndrip and free throughfall. This tends to increase the small-scale spatial variation of the chemical composition of throughfall as compared to that of rainfall (Kimmins, 1987).

As observed for rainfall amounts of TDS in throughfall (represented by the EC) decreased with the storm size due to dilution as shown in Figure 13.2A for in the Korokula forest plot. Similar patterns were observed at the other sites. An impression of the magnitude of the spatial variation in ion concentrations in throughfall was obtained from an analysis of EC measurements of the throughfall collected by each of the 20 gauges. Figure 13.2B shows the standard deviations of the EC against average EC for both pre- and post-cylone throughfall data in Korokula forest. The standard deviations, taken to represent the spatial variation, showed a linear correlation with EC, suggesting that the spatial variation in throughfall composition decreased with storm size (dilution effect). The slope of the regression line through the post-cyclone data, however, was lower than that of the line through the pre-cyclone data suggesting that the spatial variation had decreased as a result of cyclone damage (Figure 13.2B).

Weighted average values of EC, pH and ion concentrations of the throughfall collected in the Tulasewa, Korokula and Koromani forest plots, and that of stemflow collected in the Tulasewa forest plot are presented in Table 13.5. Values for the cyclone event are based on single samples. Pre-cyclone throughfall samples in the Koromani forest plot were collected during the dry season only and may therefore be

Table 13.5: *Pre-, post-cyclone and cyclone EC values ($\mu S\ cm^{-1}$), pH values and ion concentrations ($mg\ l^{-1}$) of throughfall and stemflow collected in the Tulasewa, Korokula and Koromani forest plots.*

Location	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Pre-cyclone throughfall																		
Tulasewa	14	5.68	1.03	1.10	0.18	0.18	0.27	2.34	2.45	0.90	0.17	0.06	0.26	0.02	0.02	0.02	0.22	0.03
Korokula	22	5.68	2.12	1.08	0.39	0.27	0.24	4.02	3.43	1.18	0.15	0.02	0.19	0.06	0.02	0.02	0.39	0.03
Koromani	19	5.48	1.62	1.34	0.26	0.25	0.17	2.89	4.86	1.05	0.06	0.07	0.23	0.03	0.02	0.02	0.29	0.03
Cyclone throughfall																		
Tulasewa	48	5.45	6.80	1.00	0.88	0.40	0.06	12.9	0.61	2.03	0.12	0.01	0.17	0.02	0.02	0.03	0.02	0.02
Korokula	384	5.33	56.7	3.71	8.55	3.20	0.12	124.6	2.42	17.7	0.31	0.01	0.10	0.03	0.02	0.08	0.02	0.02
Koromani*	76	5.54	11.1	1.30	1.39	0.85	0.08	19.8	0.61	3.68	0.06	0.01	0.10	0.02	0.02	0.02	0.04	0.02
Post-cyclone throughfall																		
Tulasewa	10	5.76	0.77	0.91	0.13	0.13	0.16	1.51	1.61	0.60	0.14	0.05	0.15	0.05	0.02	0.02	0.10	0.03
Korokula	16	5.54	1.75	0.64	0.22	0.22	0.12	3.30	0.94	0.98	0.11	0.02	0.11	0.07	0.02	0.02	0.11	0.02
Koromani	15	5.65	1.42	0.76	0.19	0.21	0.08	2.67	2.59	1.24	0.09	0.03	0.10	0.02	0.02	0.02	0.14	0.02
Stemflow, excluding cyclone events																		
Tulasewa	36	4.38	2.81	1.79	0.43	0.32	0.36	5.18	0.30	3.14	0.12	0.06	0.11	0.08	0.04	0.03	0.24	0.08
Cyclone stemflow																		
Tulasewa	360	4.00	45.7	5.90	6.70	3.80	0.54	102.7	0.00	16.1	0.18	0.19	0.19	0.03	0.11	0.23	0.18	0.10

Fe-T: Total Fe; N-T: Total N; P-T: Total P
*: Underestimated due to errors in bulking

less representative. Although the concentrations in throughfall were higher than those in rainfall, most constituents remained close to the detection limit, implying that the errors in the presented values may still be considerable.

The increase in mean EC of throughfall compared to the corresponding rainfall could be attributed mainly to increases in the concentrations of Na, K, Cl and SO_4. The EC decreased again with distance from the ocean, corresponding with decreases in the concentrations of constituents of maritime origin. This trend was more pronounced in throughfall than that in rainfall presumably because of the more efficient trapping of sea spray by the forest canopy as compared to the rain gauge. The pH of throughfall was similar to that of the corresponding rainfall.

The higher ion concentrations in throughfall could be explained only partly by evaporation losses from the wet canopy. Leaching of ions from the canopy, in combination with the higher trapping efficiency already referred to constitute a plausible explanation for the excess concentrations. This was supported by the fact that not all constituents showed similar increases in concentrations after correction for evaporative losses (Table 13.6). The only constituent showing very little variation in these ratios between sites during both pre- and post-cyclone periods was SO_4. Ratios of 1.0 were found for the post-cyclone period, suggesting that leaching from the canopy could be considered negligible. Hence SO_4 may be considered to be a conservative constituent and the observed increases in concentrations of SO_4 in pre-cyclone throughfall compared to those in corresponding rainfall may be attributed to the higher trapping efficiency of the forest canopy compared to the rain gauge (Miller *et al.*, 1976; Parker, 1983). The ratios of SO_4 concentrations in throughfall and rainfall suggested that the actual atmospheric nutrient inputs to the forest during the pre-cyclone period were

Table 13.6: *Ratios of ion concentrations in throughfall (after correction for losses due to evaporation) to those in rainfall in the Tulasewa, Korokula and Koromani forest plots for the pre- and post-cyclone periods and for the cyclone event.*

Location	EC	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Pre-cyclone period																	
Tulasewa	1.5	1.3	2.8	2.4	1.2	0.8	1.5	0.4	1.3	0.8	2.4	4.3	0.4	0.8	0.8	1.5	1.1
Korokula	2.3	2.1	7.9	4.9	2.5	0.8	2.2	2.4	1.5	1.2	1.0	3.2	0.9	0.8	0.8	1.0	1.2
Koromani	1.8	1.4	11.2	3.1	2.4	0.9	1.5	4.0	1.4	0.6	2.9	2.5	0.8	0.7	0.8	1.1	1.3
Cyclone Sina																	
Tulasewa									Not available								
Korokula	3.2	2.9	4.7	3.5	4.0	0.8	3.5	3.3	3.2	3.9	0.8	1.7	0.5	0.8	3.3	0.1	0.8
Koromani									Not available								
Post-cyclone period																	
Tulasewa	1.8	1.2	3.2	1.9	2.0	0.5	1.2	1.6	1.0	1.0	1.9	2.6	0.7	0.6	0.9	0.5	0.9
Korokula	1.7	2.1	3.6	3.3	2.2	0.2	1.9	1.1	1.0	0.2	0.9	1.9	1.2	0.8	0.9	0.1	0.9
Koromani	1.5	1.7	4.6	2.9	2.5	0.2	1.4	2.4	1.0	0.6	0.9	1.7	0.7	0.6	0.9	0.3	0.9

31–45% higher than those based on rain gauge sampling and given in Table 13.4. The high ratio associated with the cyclone event at Korokula indicated that the interception of sea spray by the forest was three times larger than that caught by the rain gauge. Therefore the atmospheric inputs during cyclone Sina, as given in Table 13.4, were seriously underestimated.

Again assuming that SO_4 behaved conservatively, leaching of ions from the canopy occurred if their ratios exceeded that for SO_4 (Table 13.6). In this way leaching of K, Mg and Si was observed at all sites, although not everywhere at the same rate, during both the pre- and post-cyclone periods. Leaching of K also seemed to increase with forest age, whereas the opposite was observed for Si. Leaching of Mg was pronounced most in the Korokula forest plot. However, the high ratio found for K in Koromani forest may reflect differences in the periods of sampling for throughfall (dry season) and rainfall (dry and wet season). Otherwise, both pre- and post-cyclone leaching rates were fairly similar in the Korokula and Koromani forest plots. The data for the Tulasewa forest plot indicated that Ca had not been leached from the canopy during the pre-cyclone period, whereas the leaching rate was similar to those observed at the other sites during the post-cyclone period. Leaching of Na and Cl was highest in Korokula forest and occurred at much lower rates in Tulasewa and Koromani forests. PO_4 was leached from the canopy in Tulasewa and Koromani forests, but for some unknown reason (biological activity?) not in Korokula forest.

Concentrations of NO_3, PO_4, Al, total Fe, Mn and total P in both rainfall and throughfall were frequently below the detection limits and their ratios may therefore not accurately reflect the actual enrichments in throughfall. Concentrations of NH_4, and occasionally NO_3, in throughfall were lower than those in rainfall after correction for evaporative losses. However, it is unlikely that NH_4 or NO_3 were taken up by the canopy. Therefore, the measured concentrations were either too high in rainfall, or concentrations were reduced in throughfall as a result of biological activity (*e.g.* uptake by algae) in the throughfall gauges (Bruijnzeel, 1983a; Ridder *et al.*, 1985). The use of the corresponding ratio for total N may therefore be more accurate for the determination of leaching. Pre- and post-cyclone patterns for the latter were quite different (Table 13.6) and suggested little leaching before the cyclone and indeed net absorption of N after the event.

A reduction in the leaf area surface (Section 11.3.6) as a result of cyclone damage is likely to reduce the amount of dry deposition intercepted by the canopy and will increase the amount of free throughfall. This would result in lower evaporation from the forest canopy during rainfall (Section 6.4) and also reduce the amount of nutrients washed from the canopy. Therefore concentrations in throughfall collected after cyclone Sina were expected to be lower than those observed before the temporary defoliation. Such lower concentrations were indeed observed for constituents of maritime origin associated with dry deposition (*e,.g.* Na, Cl) as well as for constituents subject to leaching (*e.g.* K, Si, total N).

Stemflow remains in contact with the canopy and stem for a longer period of time than crowndrip and ion concentrations should consequently be higher in the former (Parker, 1983). Stemflow was measured in Tulasewa forest only and records began shortly before the passage of cyclone Sina. As such the pre- and post-cyclone data were pooled. Ion concentrations in stemflow were indeed substantially higher than in throughfall with the exception of HCO_3 (which decreased as a result of the low pH), NO_3, Si and total N (Table 13.5). The lower concentration of Si in stemflow indicates that this ion may be leached from the foliage rather than from woody components. Concentrations in stemflow collected after cyclone Sina again reflected the effect of interception of sea spray by the vegetation (Table 13.5).

The total amounts of nutrients reaching the forest floor in throughfall and stemflow, and the contributions from canopy wash to the totals are given in Table 13.7. Large differences were observed between the sites, both for the pre-and post-cyclone periods. The largest increases with respect to atmospheric inputs were observed for K, as is generally reported from the literature for both temperate and tropical forests (Parker, 1983; Forti and Neal, 1992; Burghouts, 1993).

This canopy wash represents the transfer of nutrients from the canopy and stems to the forest floor and was calculated by substracting the atmospheric inputs from the totals reaching the forest floor in throughfall and stemflow (Parker, 1983). Estimates of nutrient inputs via stemflow in the Korokula and Koromani forest plots were obtained by multiplying the totals in throughfall for these forests with the ratio of the nutrient totals in stemflow to those in throughfall obtained for the Tulasewa forest site. The canopy wash data clearly showed which constituents were leached from the canopy and which were not (Table 13.7).

Although stemflow amounted to less than 2% of corresponding throughfall, relatively high concentrations of Na, K, Mg, Ca NH_4, Cl, SO_4 and total P in stemflow resulted in relative contributions of nutrients in stemflow being higher than that. Values ranged from 2% to 6% of the totals in throughfall. Stemflow reaches the forest floor in an area close to the stem and these nutrients may therefore be immediately available for uptake by tree roots (*cf.* Herwitz, 1986). Stemflow may therefore be an important source of nutrients for the tree.

13.5 Chemical Composition of Litter Percolates

Litter decomposition rates and the patterns of release of nutrients from decomposing litter were discussed earlier in Section 12.4. Two processes govern the transfer of nutrients from the litter layer to the underlying soil. The first process is physical,

Table 13.7: *Estimated total amounts of nutrients (kg ha^{-1}) in throughfall and stemflow, as well as amounts washed from the canopy (kg ha^{-1}) for various periods. Corresponding totals of throughfall and stemflow (both labelled as TF) are given for comparison.*

Location	TF	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Totals in pre-cyclone throughfall																	
Tulasewa	1366	14.0	15.0	<2.4	<2.4	<3.7	31.9	33.5	<12.3	<2.3	<0.8	3.5	<0.3	<0.3	<0.3	3.1	<0.5
Korokula	1138	24.2	12.3	4.5	<3.0	2.8	45.8	39.1	<13.5	<1.7	<0.3	2.2	<0.6	<0.2	<0.2	9.4	<0.8
Koromani	1341*	21.7	17.9	<3.4	<3.3	2.2	38.7	65.1	<14.1	<0.8	0.9	3.0	<0.4	<0.3	<0.3	3.8	<0.4
Totals in cyclone throughfall																	
Tulasewa	208	14.1	2.1	1.8	0.8	0.1	26.9	1.3	4.2	0.2	<0.0	0.4	<0.0	<0.0	0.1	<0.0	<0.0
Korokula	164	93.0	6.1	14.0	5.2	0.2	204.3	4.0	29.0	0.5	<0.0	<0.2	0.0	<0.0	0.1	<0.0	<0.0
Koromani	166*								Not available								
Totals in post-cyclone throughfall																	
Tulasewa	1439	11.1	13.1	<1.8	<1.9	2.3	21.7	23.2	<8.7	<2.1	<0.8	<2.2	<0.7	<0.3	<0.3	<1.5	<0.4
Korokula	975	17.1	6.3	<2.1	2.1	1.1	32.2	9.1	9.6	<1.1	<0.2	<1.1	<0.7	<0.2	<0.2	<1.1	<0.2
Koromani	956	13.6	7.2	<1.8	<2.0	0.7	25.5	24.7	11.8	<0.9	<0.2	<1.0	<0.2	<0.2	<0.2	1.3	<0.2
Pre-cyclone stemflow																	
Tulasewa	23*	0.6	0.4	<0.1	0.1	0.1	1.2	0.1	0.7	<0.0	<0.0	<0.0	<0.0	<0.0	<0.0	0.1	<0.0
Cyclone stemflow																	
Tulasewa	3.3*	1.5	0.2	0.2	0.1	0.0	3.4	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Post-cyclone Stemflow																	
Tulasewa	24.3*	0.7	0.4	<0.1	0.1	0.1	1.3	0.1	0.8	<0.0	<0.0	<0.0	<0.0	<0.0	<0.0	0.1	<0.0
Pre-cyclone canopy wash																	
Tulasewa		3.4	9.9	1.5	0.4	-0.8	10.3	-64.1	3.3	-0.5	0.5	2.7	-0.5	-0.1	-0.1	0.9	0.0
Korokula		12.5	11.0	3.6	1.8	-0.8	24.3	21.5	4.1	0.2	-0.0	1.5	-0.1	-0.1	-0.1	-0.6	0.1
Koromani		6.2	16.8	2.5	2.0	-0.2	13.2	48.6	4.5	-0.6	0.6	1.8	-0.1	-0.1	-0.1	0.2	0.1
Cyclone canopy wash																	
Tulasewa									Not available								
Korokula		74.3	5.5	12.1	4.8	0.0	177.9	2.9	24.4	0.4	0.0	0.1	-0.0	-0.0	0.1	-0.2	-0.0
Koromani									Not available								
Post-cyclone canopy wash																	
Tulasewa		2.3	9.3	1.0	1.0	-2.0	4.6	8.3	0.2	-0.1	0.4	1.4	-0.3	-0.2	-0.0	-1.4	-0.0
Korokula		10.2	4.7	1.6	1.2	-4.3	17.6	0.7	1.3	-4.1	-0.0	0.5	0.1	-0.0	-0.0	-6.4	-0.0
Koromani		6.3	5.9	1.2	1.2	-2.9	8.8	14.1	1.0	-0.7	-0.0	0.4	-0.1	-0.1	-0.0	-2.8	-0.0

*: Estimated using Gash's analytical model

Table 13.8: *Amounts of litter percolate and ion concentrations (mg l^{-1}) in litter percolate for the pre- and post-cyclone periods (weighted averages) and for the cyclone period in the Tulasewa, Korokula and Koromani forest plots.*

Location	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Litter percolate, pre-cyclone																		
Tulasewa	37	5.78	1.83	3.71	1.15	1.50	0.37	5.38	6.66	2.50	0.14	0.09	2.00	0.09	0.02	0.02	0.43	0.04
Korokula	47	5.70	3.13	2.63	2.23	1.70	0.38	8.24	6.40	3.79	0.52	0.14	1.46	0.06	0.05	0.02	0.60	0.07
Koromani	35	5.54	2.63	1.98	1.27	1.44	0.33	3.89	6.66	2.71	0.19	0.10	0.54	0.10	0.04	0.02	0.62	0.03
Litter percolate, cyclone																		
Tulasewa	135	5.87	15.5	5.02	3.25	3.60	0.40	38.0	8.54	6.59	0.05	0.04	1.40	0.04	0.02	0.09	0.23	0.03
Korokula	1570	5.19	229.0	14.1	42.3	23.1	0.38	526.1	5.49	73.4	0.05	0.02	0.62	0.02	0.03	0.61	0.29	0.03
Koromani	570	5.61	77.9	6.68	13.1	10.2	0.21	175.8	3.66	24.0	0.06	0.06	0.25	0.09	0.32	0.44	0.22	0.02
Litter percolate, post-cyclone																		
Tulasewa	38	6.07	1.51	6.94	0.70	1.25	0.43	4.24	5.55	2.30	0.38	0.94	2.09	0.06	0.02	0.02	0.48	0.33
Korokula	74	5.99	8.04	4.85	2.52	2.15	0.31	13.66	10.0	5.23	0.47	0.44	1.55	0.05	0.06	0.02	0.76	0.20
Koromani	56	6.10	4.49	4.66	1.78	2.16	0.23	8.73	8.50	3.77	1.12	0.31	0.69	0.13	0.05	0.04	0.61	0.14

Fe-T: Total Fe; N-T: Total N; P-T: Total P

involving the transport of small solid particles of decomposed litter into the topsoil by percolating water or by soil animals. Further decomposition of these particles in the soil results in the slow release of the incorporated nutrients. The second process is chemical and involves the leaching of constituents from decomposing litter, from dead soil animals and from soil animal excrements present in the litter layer (Duchaufour, 1982; Swift and Anderson, 1989). As these nutrients are already in ionic form they may be more readily taken up by the vegetation than those transported into the soil in organic matter.

As a result of dry deposition on the forest floor, evaporation of water from the forest floor (Section 6.4.2) and, most importantly, leaching of constituents from the decomposing litter, throughfall and stemflow reaching the forest floor become enriched while percolating through the litter layer (Turvey, 1974; Bruijnzeel, 1983a; Burghouts, 1993). The concentrations of ions in litter percolate collected in the Tulasewa, Korokula and Koromani forest plots during various periods of time are shown in Table 13.8. The pre-cyclone data for Koromani forest were collected during the dry season of 1990, whereas those for the other sites included the wet season as well. Because litter percolate trays were not positioned against tree stems, the samples did not include contributions from stemflow. Furthermore, some uncertainty in the concentrations was introduced by overflow of the collectors during large storms. The spatial variation in the chemical composition of litter percolate was high, depending on the thickness and composition of the litter layer, as well as on the spatial variation of the throughfall (amounts and composition, *cf.* Burghouts, 1993).

The pH of pre-cyclone litter percolate was similar to that of the corresponding throughfall at all sites, but EC and concentrations of most constituents increased. The largest increases were observed for Ca, Si, Mg, K, Cl and SO_4 (Tables 13.8 and 13.5). The relatively high concentration of K in the litter percolate in the Tulasewa forest plot as compared to the other sites may be the result of leaching from the K-rich undergrowth vegetation (Table 10.4), which died at the end of the wet season. The litter decomposition experiment (Section 12.4) indicated that P was leached rapidly after incubation of the litter bags. However, no evidence of leaching of P was found from the pre-cyclone litter percolate data. The needles used in the litter bag experiments were relatively fresh compared to those reaching the forest floor in litterfall and perhaps considerable amounts of P (and K) were already leached from dying needles and detached needles suspended in the canopy. This hypothesis is supported by the fact that leaching of P from the litter layer increased greatly after the sudden addition of fresh litter to the forest floor by cyclone Sina (Table 13.8). A similar lack of increased P concentrations in litter percolates during steady state conditions was observed for pine forest in Central Java (Bruijnzeel, 1983a) and lowland rain forest in Sabah, Malaysia, (Burghouts, 1993) using similar methodology to that of the present study.

As indicated earlier, deposition of sea spray occurred at the height of the cyclone and because most of the rainfall was recorded in the preceding 48 hours, the contribution of ions from sea spray to the litter percolate samples was overestimated at all sites due to overflow of the containers. The presented values therefore represent the concentrations during the final stage of the cyclone rather than bulk averages over the whole event. However, because leaching from the litter layer before the deposition of fresh litter by the cyclone will not have been larger than usual and because most of the sea spray will have been intercepted initially by the forest canopy rather than by the litter layer, the actual concentrations of bulk litter percolate after cyclone Sina may be expected to be only slightly higher than observed in the corresponding bulk throughfall samples.

The large deposition of fresh litter by cyclone Sina resulted in an increase in the pH of litter percolate compared to that of throughfall in the post-cyclone period (Tables 13.8 and 13.5). This suggested that protons were extracted from the percolating water in order to release other constituents from the fresh litter. The flushing of sea spray deposited on the litter and increased leaching from the fresh litter during the first month after the cyclone caused large increases in the EC of the litter percolate in the Korokula and Koromani forest plots (Table 13.8). Such large amounts of sea spray were not deposited in the Tulasewa forest plot and the EC of the litter percolate collected shortly after cyclone Sina was therefore not influenced as much (Table 13.8). However, a closer look at the nutrient concentrations in the litter percolate at this site revealed large increases in K, PO_4, total P and NO_3, all constituents which contribute little to the EC, but which must have been intimately connected with the deposition of large amounts of fresh litter by the cyclone. Similar increases in K, PO_4, total P and NO_3 were observed at the other sites but these were accompanied by corresponding increases in Na, Cl, Mg, Ca and SO_4 (sea spray) which explained the increase in the EC values observed at these sites. A possible reason for the lack of leaching of Ca and Mg from the litter layer in the Tulasewa forest plot could be that, unlike in the older forests, the decomposer community had not yet adapted to having to decompose large amounts of pine litter. As indicated earlier, the pre-cyclone litter layer at Tulasewa consisted predominantly of mission grass litter.

Estimates of the inputs of nutrients to the mineral soil are presented in Table 13.9. The volumes of litter percolate for the various periods were obtained using the model described in Section 6.4.2. By subtracting the inputs to the soil in litter percolate from the corresponding inputs to the litter layer in throughfall and stemflow, estimates were obtained for the amounts of nutrients mineralised in and leached from the litter layer.

Table 13.9: *Amounts of litter percolate (LP, in mm), associated nutrient contents (kg ha^{-1}) reaching the mineral soil and estimated amounts (kg ha^{-1}) leached at the Tulasewa, Korokula and Koromani forest plots during various periods.*

Location	LP	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Totals in pre-cyclone litter percolate																	
Tulasewa	1223	22.3	45.3	14.0	18.3	<4.6	65.8	81.5	30.6	<1.7	1.1	24.4	<1.0	<0.2	<0.2	5.2	<0.5
Korokula	1014	31.8	26.7	22.6	17.2	3.9	83.5	64.9	38.4	<5.3	<1.4	14.8	<0.6	<0.5	<0.2	6.1	<0.7
Koromani	1179	31.0	23.3	14.9	16.9	3.9	45.9	78.6	31.9	<2.3	<1.2	6.4	<1.2	<0.5	<0.2	7.3	<0.4
Totals in cyclone litter percolate																	
Tulasewa	215	33.2	10.8	7.0	7.7	0.9	81.6	18.4	14.2	<0.1	0.1	3.0	0.1	<0.0	0.2	0.5	0.1
Korokula	150	344	21.1	63.4	34.6	0.6	789	8.2	110.1	0.1	0.0	0.9	<0.0	0.0	0.9	0.4	0.0
Koromani	156	122	10.4	20.4	15.9	0.3	274	5.7	37.5	0.1	0.1	0.4	0.1	0.5	0.7	0.3	0.0
Totals in post-cyclone litter percolate																	
Tulasewa	1290	19.5	89.5	9.0	16.1	5.6	54.7	71.6	<29.6	<4.9	12.1	27.0	<0.8	<0.2	<0.2	6.2	4.2
Korokula	853.2	68.6	41.3	21.5	18.4	2.6	117	85.5	44.6	<4.0	3.7	13.2	<0.4	0.5	<0.2	6.5	1.7
Koromani	817.3	36.7	38.1	14.6	17.7	1.8	71.4	69.5	30.8	<9.1	<2.6	5.6	<1.1	<0.4	<0.3	5.0	1.2
Pre-cyclone litter mineralisation																	
Tulasewa		7.7	29.9	11.5	15.8	0.8	32.7	47.9	17.5	-0.7	0.3	20.9	0.8	-0.0	-0.0	2.1	0.1
Korokula		6.5	14.0	17.9	14.1	1.0	36.1	25.7	24.1	3.6	1.1	12.6	-0.0	0.3	-0.0	1.6	0.3
Koromani		8.3	4.9	11.3	13.5	1.6	5.7	13.3	17.0	1.4	0.3	3.3	0.8	0.2	-0.0	3.4	-0.1
Cyclone litter mineralisation																	
Tulasewa		17.6	8.5	4.9	6.8	0.7	51.4	17.1	9.4	-0.1	0.1	2.6	0.0	-0.0	0.1	0.4	0.0
Korokula		241	14.4	47.7	28.5	0.3	559	4.3	77.5	-0.4	0.0	0.8	-0.0	0.0	0.8	0.4	0.0
Koromani									Not available								
Post-cyclone litter mineralisation																	
Tulasewa		7.8	76.0	7.1	14.1	3.2	31.7	48.3	20.2	2.8	11.3	24.7	0.1	-0.0	-0.1	4.6	3.9
Korokula		50.5	34.9	19.3	16.1	1.4	82.5	76.3	34.2	2.9	3.5	12.1	-0.3	0.3	-0.0	5.4	1.5
Koromani		22.3	30.6	12.7	15.6	1.1	44.4	44.7	17.9	8.2	2.3	4.7	0.9	0.3	0.1	3.6	1.0

13.6 Chemical Composition of Soil Moisture

Various chemical and physical processes in the soil act to change the chemical composition of infiltrating water. Removal of soil moisture by evapotranspiration results in increased concentrations of all constituents, proportional to the amount of moisture removed. Further changes are caused by biological activity (*e.g.* selective uptake and exudation of nutrients by the vegetation), buffering reactions with the soil exchange complex, precipitation of minerals from the soil solution, contributions by decaying organic matter and weathering or dissolution of minerals (Duchaufour, 1982). The largest changes usually occur in the root zone, although some processes are particularly active in the subsoil (notably weathering). Samples of the soil solution obtained with suction lysimeters may not accurately reflect the chemical composition of the ambient soil moisture due to interaction with the ceramic material of the cup and the concentrations of certain constituents presented below may therefore deviate from the actual concentrations in the soil moisture (see also Section 13.2).

The spatial variation in soil moisture composition was accounted for by installing 3–4 sets of lysimeters at the same depth within a plot. Variations in EC of the moisture collected from the samplers provided a first indication of the spatial variation within the plot at each depth. Values during the pre-cyclone period varied between 22–48 μS cm^{-1} in both top- and subsoil in the Tulasewa forest plot, between 41–117 μS cm^{-1} and 94–180 μS cm^{-1} in top- and subsoil in the Korokula forest plot, respectively, and between 48–58 μS cm^{-1} and 44–73 μS cm^{-1} in top- and subsoil in the Koromani forest plot, respectively. Temporal variations were small.

Post-cyclone EC values in the Korokula forest plot were much higher than the pre-cyclone values, and decreased from a maximum of 700–800 μS cm^{-1} shortly after cyclone Sina in January to 110–170 μS cm^{-1} in March, 1991, as the salts deposited during the passage of the cyclone were rapidly leached. The change was less pronounced in Koromani forest where the EC decreased from 54–156 μS cm^{-1} to 59–110 μS cm^{-1} over the same period. Only a very slight increase in EC was observed at Tulasewa forest following the passage of cyclone Sina.

The EC, pH and ion concentrations in pre- and post-cyclone soil solutions (volume weighted averages) for the various forest sites are presented in Table 13.10. The dominant ions in the soil solution were Cl and Na, followed by Si, HCO_3, SO_4 and Mg. Concentrations of all ions, with the exception of K, were highest in the Korokula forest plot, where the soil contained the largest amount of weatherable minerals (Section 4.4). Gradients in ion concentrations in the soil solution with soil depth were small in the Tulasewa and Koromani forest plots. However, the large contrast in chemical properties of the top- and subsoil in the Korokula forest plot (Section 4.4) was reflected in the composition of soil moisture which showed considerable increases in concentrations of Na, Mg, Cl, HCO_3 and SO_4 with depth (Table 13.10).

Post-cyclone ion concentrations at the Korokula and Koromani forest plots, which were both situated relatively close to the ocean, reflected the large inputs of sea salt by cyclone Sina, with large increases in concentrations of Na, Cl, Mg and Ca. Concentrations of K increased at all sites which may be explained by leaching of K from the large quantities of fresh litter deposited by the cyclone. No such increase was observed for PO_4 or total P, the concentrations of which remained below or just above the detection limit, although the needle decomposition data indicated that P would be released shortly after the deposition of the needles on the forest floor (Section 12.4). This finding also stands in contrast to the observed rises in concentrations of PO_4 in litter percolate after the cyclone (Table 13.8). Whilst P is known to become rapidly

Table 13.10: *Average pre- and post-cyclone values of EC ($\mu S\ cm^{-1}$), pH and ion concentrations ($mg\ l^{-1}$) in top- and subsoil moisture in the Tulasewa, Korokula and Koromani forest plots.*

Location	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Topsoil moisture, pre-cyclone																		
Tulasewa	32	5.73	3.31	0.19	1.00	0.37	0.18	6.22	4.92	1.60	0.28	0.02	3.54	0.05	0.02	0.02	0.05	0.02
Korokula	82	5.93	8.08	0.09	2.91	1.49	0.20	14.30	5.28	3.92	6.55	0.03	7.38	0.05	0.02	0.02	0.48	0.02
Koromani	52	5.30	6.12	0.12	1.03	0.67	0.20	7.64	2.71	2.90	6.73	0.03	2.18	0.08	0.05	0.05	0.23	0.02
Subsoil moisture, pre-cyclone																		
Tulasewa	30	5.75	3.08	0.22	0.88	0.13	0.12	4.51	6.62	0.80	0.17	0.02	3.68	0.05	0.04	0.02	0.06	0.03
Korokula	141	6.27	18.21	0.12	4.57	1.28	0.21	25.40	24.86	6.32	7.50	0.04	6.54	0.05	0.03	0.02	0.37	0.04
Koromani	52	4.88	7.35	0.17	0.66	0.29	0.20	10.64	1.64	1.58	4.08	0.02	1.89	0.07	0.05	0.05	0.22	0.02
Topsoil moisture, post-cyclone																		
Tulasewa	33	5.95	3.44	0.28	0.95	0.32	0.19	6.71	2.91	1.38	0.14	0.02	2.82	0.05	0.02	0.02	0.11	0.02
Korokula	321	6.17	23.17	0.34	17.4	9.81	0.24	93.36	6.91	7.10	5.16	0.02	7.89	0.06	0.02	0.03	0.31	0.02
Koromani	106	4.85	12.89	0.55	2.73	2.28	0.35	30.69	1.47	1.33	2.13	0.04	3.83	0.06	0.04	0.02	0.34	0.03
Subsoil moisture, post-cyclone																		
Tulasewa	33	6.01	4.14	0.19	1.14	0.12	0.11	7.37	4.56	0.93	0.08	0.02	3.35	0.08	0.02	0.02	0.05	0.02
Korokula	328	6.45	35.64	0.25	15.7	2.75	0.11	94.82	8.22	5.02	1.92	0.02	6.83	0.05	0.02	0.02	0.12	0.02
Koromani	79	5.83	12.44	0.23	0.97	0.71	0.18	20.84	1.05	0.98	2.92	0.02	2.71	0.06	0.02	0.02	0.10	0.03

Fe-T: Total Fe; N-T: Total N; P-T: Total P

immobilized in many tropical soils due to complexing with various organic, Al, and Fe compounds (Sanchez, 1976), the observed lack of response of PO_4 concentrations in soil moisture may well be an artefact of the method of sampling with ceramic cups which tends to underestimate the concentrations of P (Zimmermann *et al.*, 1978). Post-cyclone concentrations of NO_3 and total N were lower than pre-cyclone ones, which may be explained by the uptake of N by the forest for the regeneration of needles, because N is only slowly released from decomposing needles (Section 12.4). The effect of the cyclone on the concentrations of NH_4 was inconclusive, with little change in the concentrations in top- and subsoil moisture in the Tulasewa forest plot, and relatively large changes in the top- and subsoil at the Koromani plot. Increases of the NH_4 concentration were observed in the topsoils in the Korokula and Kormani forests, whereas concentrations decreased in the subsoils.

Steudler *et al.*, (1991) observed increases in concentrations of NH_4, as well as in those of NO_3, in the surface soils four months after hurricane Hugo badly damaged natural rain forests in Puerto Rico. The hurricane also increased the net N-mineralization in the surface soil. No data was presented for the subsoils.

13.7 Nutrient Exports in Water Leaving the Forest Plots

13.7.1 Nutrient Exports from the Forest Plots

Nutrient exports from the forest plots in drainage water were calculated by combining amounts of water leaving the site as drainage (D, Section 6.6) and ion concentrations

Table 13.11: *Estimates of pre- and post-cyclone nutrient exports (kg ha^{-1}) from the Tulasewa, Korokula and Koromani forest plots in drainage (D, in mm).*

Location	D+Q	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Pre-cyclone period																	
Tulasewa	167	5	0.4	1.5	0.2	0.2	8	11	<1.3	<0.3	<0.1	6.1	<0.1	<0.1	<0.1	<0.2	<0.1
Korokula	194	35	<0.3	8.9	2.5	0.4	49	48	12.3	14.6	<0.1	12.7	<0.1	0.1	<0.1	0.7	0.1
Koromani	322	24	0.5	2.1	0.9	0.6	34	5	5.1	13.1	<0.1	6.1	<0.3	<0.2	<0.2	0.7	<0.1
Post-cyclone period																	
Tulasewa	877	36	1.7	10.0	<1.1	1.0	65	40	8.2	<0.7	<0.2	29.3	<0.7	<0.2	<0.2	<0.5	<0.2
Korokula	211	75	0.5	33.1	5.8	0.2	200	17	10.6	4.1	<0.1	14.4	<0.2	0.0	<0.1	0.3	<0.1
Koromani	241	30	0.6	2.3	1.7	0.4	50	3	2.4	7.0	<0.1	6.5	<0.2	<0.1	<0.1	0.3	<0.1

in soil moisture extracted from the subsoil. The results are presented in Table 13.11. The calculations suffered from various uncertainties, ranging from the errors in the ion concentrations in the soil solution discussed previously, to those in estimated amounts of water leaving the respective sites as drainage. Lateral subsurface flow is likely to occur at all sites due to the large contrast in the hydraulic conductivity of the top- and subsoils (Section 4.3.3). The composition of this lateral (subsurface) flow may differ from that of water removed by deeper drainage (Bruijnzeel, 1983a) and this will result in errors in the calculated nutrient exports whenever gradients of ion concentrations in the soil solution with depth are considerable (as in the Korokula forest plot). In addition, soil moisture passing through the weathering zone may attain higher concentrations as ions are released by weathering (Eernisse, 1993). Because the lysimeter cups could not be placed in this zone, exports of nutrients may have been underestimated further. This is supported by the fact that pre-cyclone concentrations of Na, Ca, Mg and Si in moisture collected in the subsoil just above the weathering zone in the Korokula forest plot were much higher than those at the other sites where the cups were well above the weathering zone. However, this will only be true to the extent that the water indeed travels through the zone of rotten rock rather than being deflected laterally just above it due to the associated drop in hydraulic conductivity. Therefore, although the exports of nutrients from the sites as given in Table 13.11 may be underestimated as a result of these uncertainties, the effect may be limited (*cf.* Section 13.7.2), but further work is necessary on this subject is necessary (Bruijnzeel, 1991). The annual nutrient yield values of the study plots are plotted against the annual runoff in Figure 13.3 for comparison with data obtained in tropical forests elsewhere. A short discussion is given in Section 13.7.4.

Both pre- and post-cyclone exports were highest in the Korokula forest plot. The high amount of water exported from the Tulasewa forest plot during the wet post-cyclone period resulted in high exports from this site compared to the pre-cyclone exports, although the ion concentrations in the soil solution had changed little. Post-cyclone exports from the Koromani plot were only slightly higher than pre-cyclone values (Table 13.11).

13.7.2 Nutrient Exports in Streamflow from the Oleolega Catchment

The water budget of the forested Oleolega catchment and the pre-cyclone atmospheric nutrient inputs have been discussed in Section 8.3 and 13.3, respectively. To complete the catchment nutrient input – output budget, the annual export of nutrients in streamflow for the period January 4, 1990 – January 4, 1991, will be quantified here. During this period 161 mm of water was discharged as baseflow during rainless periods, whereas another 140 mm was discharged during storms (both as base- and quickflow). The data presented in the following are largely based on the work of Schellekens (1992).

Nutrient exports in streamflow are strongly dependent on amounts of streamflow (Likens *et al.*, 1977), which in turn reflect amounts and distribution of rainfall (Section 8.3). To obtain a representative estimate of nutrient output, it is important that the rainfall regime during the observation period is comparable to the long-term average (Likens *et al.*, 1977; Bruijnzeel, 1983a). Long-term average monthly rainfall totals for Nabou Station were presented in Table 6.2. Total rainfall over the period under consideration (1875 mm) was about 11% above the long-term average (1695 mm). Furthermore, the monthly distribution differed from the long-term average as well, with below average rainfall in February (92 mm), and above average rainfall in June (140 mm), August (228 mm) and November (313 mm). The effect of such deviations from the long-term average conditions on nutrient outputs is difficult to establish, but is considered to remain within the errors associated with the discharge measurements and the analytical procedures. In addition, there may be slight topographic and orographic effects as Nabou station is situated at a lower elevation than than the Oleolega catchment. The basic hydrological data collected at the Oleolega catchment were not adjusted therefore.

The nutrient output from a catchment for a given period can be obtained by multiplying discharge with the average nutrient concentrations of the streamwater samples collected during this period, provided that fluctuations in concentrations with variations in discharge remain small (Likens *et al.*, 1977). Whilst this is generally true during baseflow conditions, much larger variations are usually observed during stormflow conditions when streamflow consists of contributions from various sources (Bruijnzeel, 1983a; Ward, 1984). Various discharge–solute concentration relationships have been proposed in the literature (Hall, 1968; Johnson *et al.*, 1968) to overcome this problem. In the following sections the chemical composition of the Oleolega Creek during baseflow and stormflow conditions will be discussed separately.

Chemical Composition of Baseflow

Baseflow samples were collected over the normal range of baseflow discharge (0.01–0.04 mm h^{-1}) and the average discharge at sampling (0.02±0.01 mm h^{-1}, range 0.009–0.030 mm h^{-1}) was similar to the weighted average for the whole period. The average concentrations obtained from these samples are presented in Table 13.12. Concentrations of PO_4, total P, Al, and to a lesser extent NO_3 and total N, were often below the detection limits and the resulting averages must therefore be too high. The dominant ion in streamflow was HCO_3, which accounted for 29% of the sum of ions, followed by Si (23%), Na (22%), Cl (9%), Mg (8%), SO_4 (4%), and Ca (3%). Contributions to the sum of ions by the other constituents were less than 1%. The standard deviations of the concentrations of the major ions were within, or close to, the range of analytical

Table 13.12: *Mean chemical composition of baseflow and stormflow (in mg l^{-1}; SD: standard deviation; n: number of samples) in the Oleolega catchment and the ratio of concentrations in baseflow to those in precipitation (Q/P ratio).*

	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Pre-cyclone Baseflow, December 25, 1989 - November 26, 1990																		
Mean	91	6.62	10.54	0.24	3.82	2.79	0.22	6.19	36.32	7.47	0.16	0.02	13.7	0.06	0.35	0.18	0.08	0.02
SD	4	0.10	0.23	0.11	0.22	0.21	0.17	0.31	2.21	0.74	0.13	0.01	0.6	0.03	0.06	0.04	0.05	0.01
n	20	20	20	20	20	20	20	20	20	20	19	19	20	20	16	16	20	20
Q/P ratio	12.3	1.2	17.2	1.6	55.0	28.6	0.8	5.0	6.2	8.6	0.9	0.6	146	1.0	7.8	5.7	0.5	0.9
Pre-cyclone Stormflow, January 14 - November 27, 1990																		
Mean	87	6.58	9.64	0.81	3.63	2.63	0.18	6.07	31.02	6.82	0.68	0.02	12.2	0.05	0.29	0.14	0.09	0.02
SD	7	0.13	0.58	0.38	0.44	0.42	0.12	0.68	4.51	0.76	1.11	0.02	1.4	0.06	0.10	0.05	0.06	0.00
n	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Comparison between pre-cyclone baseflow (A) and stormflow (B) concentrations																		
A <> B	>**	>*	>***	<***	>*	>*	ns	ns	>***	>***	<**	ns	>***	ns	>**	>***	ns	ns

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

errors (Table 13.2). The baseflow composition may therefore be considered constant during the pre-cyclone period, although a seasonal trend could be observed with somewhat lower than average concentrations during the wet season, and somewhat higher concentrations during the dry season.

The ratio of concentrations in streamflow (Q) to those in rainfall (P) provides a good indication of how the composition of the water is altered when passing through the ecosystem (Likens *et al.*, 1977). Evapotranspiration reduced the amount of water leaving the Oleolega catchment by a factor 6.4 (Section 8.3) compared to rainfall input. If this would be the only process acting to change the composition of the rain water then concentrations in streamflow would all increase by a factor 6.4. The Q/P ratios for HCO_3 and Mn were fairly close to this value, but the ratios for the other ions deviated substantially, indicating that other processes (*e.g.* weathering, biogeochemical processes) were acting to change the concentrations of these ions. The Q/P ratios for K, NH_4 and total N were low, suggesting that these ions were accumulating in the catchment, presumably in the pine biomass for this actively growing forest. Similar ratios would be expected for NO_3, PO_4 and total P, as these constituents are also strongly influenced by biolological processes (Waring and Schlesinger, 1985), but no conclusions could be drawn in this respect because their concentrations were below the detection limits in both rainfall and stream water. The same was true for Al. Q/P ratios for Si, Mg, Ca and Na were high, however, indicating that these nutrients were leached from the catchment. The most likely source of these elements is weathering of the parent rock and primary minerals in the soil (Section 4.4).

Pre-cyclone data on the chemistry of the baseflow from the Oleolega catchment, and from several other forested and grassland catchments in the same area, collected during the dry season of 1990, are given in Table 13.13. The data clearly indicate that afforestation did not result in significant changes in the baseflow concentrations of K, Total N, NO_3, PO_4, Total P and Mn (α= 0.05). Total P was just above or below the detection limit at all sites and exports of this element are therefore low both from grassland and forest catchments. Concentrations of NH_4 were significantly higher

Table 13.13: *Means and standard deviations of the EC, pH and ion concentrations in baseflow (mg l^{-1}) from samples (n= sample size) collected at various locations in and around the Oleolega catchment. Levels of significance (*Student' t *test) for differences between means added.*

Location	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Pre-cyclone baseflow Oleolega Creek, Forested, A																		
Average	91	6.61	10.2	0.36	3.9	2.9	0.18	6.5	35.0	7.4	0.28	0.02	12.4	0.04	0.36	0.19	0.07	0.02
SD	*4*	*0.16*	*0.7*	*0.18*	*0.2*	*0.2*	*0.17*	*0.6*	*3.4*	*0.7*	*0.27*	*0.02*	*1.1*	*0.01*	*0.10*	*0.06*	*0.06*	*0.00*
n	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Pre-cyclone baseflow Oleolega Creek, downstream at Junction with Kubuna Creek, Forested, B																		
Average	161	6.90	12.3	0.45	8.3	12.0	0.31	9.3	82.0	7.4	0.15	0.01	9.8	0.04	0.05	0.02	0.04	0.02
SD	*10*	*0.09*	*0.7*	*0.06*	*0.5*	*0.8*	*0.23*	*0.5*	*5.4*	*0.7*	*0.09*	*0.01*	*0.4*	*0.01*	*0.03*	*0.00*	*0.02*	*0.00*
n	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5
Pre-cyclone Naruku Creek, Forested, C																		
Average	131	6.47	12.4	0.70	5.1	6.7	0.46	10.3	50.4	9.5	0.56	0.01	10.0	0.15	1.61	1.01	0.12	0.02
SD	*26*	*0.17*	*1.0*	*0.74*	*1.1*	*1.5*	*0.31*	*1.0*	*11.0*	*4.9*	*0.58*	*0.00*	*1.7*	*0.14*	*2.05*	*0.29*	*0.09*	*0.00*
n	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2
Pre-cyclone baseflow Ividamu Creek, Grassland, D																		
Average	137	6.39	14.4	0.57	5.9	6.2	0.16	12.6	63.5	2.4	0.25	0.04	10.1	0.07	1.22	0.71	0.11	0.02
SD	*15*	*0.21*	*0.7*	*0.47*	*1.2*	*1.8*	*0.04*	*1.2*	*12.5*	*1.3*	*0.32*	*0.02*	*1.2*	*0.07*	*1.03*	*0.65*	*0.11*	*0.00*
n	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Significance of differences between means																		
A<>B	<***	<***	<***	ns	<***	<***	ns	<***	<***	ns	ns	ns	>***	ns	>***	>***	ns	ns
A<>C	<**	ns	<***	ns	<**	<***	<*	<***	<**	ns	ns	ns	>**	<*	ns	<***	ns	ns
A<>D	<***	>*	<***	ns	<***	<***	ns	<***	<***	>***	ns	ns	>**	ns	<*	<*	ns	ns
C<>D	ns	ns	<***	ns	ns	ns	>**	<**	ns	>**	ns	<*	ns	ns	ns	ns	ns	ns

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

in baseflow from the forested Naruku catchment than from the Ividamu grassland catchment. However, this may reflect local factors because the difference between the means for the Oleolega and Ividamu catchments were not significant. Differences in the Mg and Ca concentrations from the Naruku and Ividamu catchments were not significant, suggesting again that the impact of afforestation on the concentrations of these nutrients in baseflow was negligible, and that the observed differences for the other sites must be due to differences in geology, rather than vegetation.

However, concentrations of SO_4 in baseflow from the forested catchments were significantly higher than those from the grassland catchment, whereas concentrations of Na and Cl were significantly lower. These differences could not be attributed to differences in geology and must therefore reflect differences in the biogeochemical processes in forest and grassland. Whilst the rise in SO_4 concentration might be related to higher bacteriological activity in the forested areas the drop in Na and Cl is more difficult to explain. After all, a positive change would have been expected in view of the larger trapping efficiency for maritime aerosols of the forest canopy (*cf.* Section 13.4 on throughfall chemistry). The only explanation that one is left with at present would be accumulation of Na and Cl in the biomass of the forest but we lack the data to substantiate this supposition.

A seasonal trend was observed in the pre- and post-cyclone baseflow concentrations of PO_4, Total N and K from the grassland catchment, with relatively high levels at the end of the dry season, and low levels at the end of the wet season. The pattern corresponded with the seasonal growth pattern of the grassland vegetation (Chapter 10). No such trends were observed for the forested catchments.

13.7.3 Chemical Composition of Stormflow

The average chemical composition of stormflow is much harder to establish, because stormflow is a mixture of baseflow, channel precipitation and various other contributions from the hillslope (*e.g.* saturated and Hortonian overland flow, subsurface stormflow). Furthermore, the contribution of each of these components is likely to change with antecedent moisture conditions, storm size, rainfall intensity, and the areal distribution of rainfall, resulting in relatively large variations in streamflow ion concentrations during a storm. To complicate the matter further, the various ions respond differently to changes in the discharge, and ion concentrations for a specific discharge in the rising limb of the hydrograph may be different from those at the same discharge in the falling limb (hysteresis, Hall, 1968).

During the pre-cyclone period insufficient stormflow samples were collected to express ion concentrations as a function of discharge or EC, for which continuous records were available. Assenberg (1993) observed that stormflow concentrations of Na, Mg, Ca, NH_4, Cl, HCO_3, Si and Mn at Oleolega were lower than those in baseflow, and attributed this to dilution of the streamwater by precipitation and overland flow. On the other hand, concentrations of K and NO_3, and to a lesser extent Cl, seemed to increase during the rising stage, reaching maximum values at discharges below 10 mm h^{-1}, followed by a decrease at higher discharges. This behaviour was attributed to leaching of the litter layer and topsoil. Concentrations of SO_4 did not show a clear dependency on the discharge. Although the data set of Assenberg (1993) consisted of samples collected shortly after the passage of cyclone Sina and during the subsequent harvesting of the destroyed plantation (December, 1990 – May, 1991), the observed relationships may generally hold for the pre-logging period as well, since the impact of logging at that stage was limited (see also Section 15.6).

Table 13.14: *Annual export of nutrients from the Oleolega catchment in baseflow and stormflow, as well as the total. The totals were obtained by multiplying the total amounts of base- and stormflow (mm) over the period January 4, 1990 – January 4, 1991, with the corresponding pre-cyclone ion concentrations (mg l^{-1}.*

	Q	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Annual Export in Baseflow [kg ha-1]																	
Total	160.9	17.0	0.39	6.1	4.5	0.36	10.0	58.4	12.0	<0.26	<0.03	22.0	<0.10	0.57	0.30	<0.12	<0.03
SD		0.4	0.17	0.4	0.3	0.27	0.5	3.6	1.2	0.20	0.02	0.9	0.05	0.09	0.07	0.08	0.01
Annual Export in Stormflow [kg ha-1]																	
Total	140.1	13.5	1.13	5.1	3.7	0.25	8.5	43.5	9.6	0.95	<0.02	17.1	<0.07	0.41	0.19	<0.13	<0.03
SD		0.8	0.54	0.6	0.6	0.17	1.0	6.3	1.1	1.56	0.02	1.9	0.09	0.13	0.07	0.08	0.00
Total Annual Export [kg ha-1]																	
	301.0	30.5	1.52	11.2	8.2	0.61	18.5	101.9	21.6	<1.21	<0.05	39.1	<0.17	0.98	0.49	<0.25	<0.06

Average EC, pH and ion concentrations for pre-harvesting stormflow samples are given in Table 13.12. The samples were collected mostly at relatively low discharges, averaging 0.06±0.08 mm h^{-1} (range 0.01–0.3 mm h^{-1}), as it was too dangerous to collect samples during the two cyclone events when 77% of the annual stormflow total was produced (besides, the area was inaccessible at that time). The weighted average stormflow discharge amounted to 0.25 mm h^{-1} including cyclone events, but only 0.08 mm h^{-1} when these were excluded. As such, the concentrations of ions that were positively correlated with discharge have probably been overestimated, whereas those for K and NO_3 may have been underestimated.

Comparison of the average ion concentrations in pre-cyclone stormflow with those in the pre-cyclone baseflow confirmed the findings of Assenberg (1993), with significantly lower concentrations of Na, Mg, Ca, HCO_3, Si and Mn, and significantly higher concentrations of K and NO_3 in the former. The stormflow concentration of SO_4 was significantly lower than the baseflow concentration suggesting that SO_4 was also subject to dilution by channel precipitation or hillslope runoff.

13.7.4 Nutrient Exports from the Oleolega Catchment

The baseflow composition may be considered relatively constant, and a fairly reliable estimate of the associated nutrient output from the catchment can thus be obtained by multiplying the average pre-cyclone concentrations with the baseflow total, excluding the baseflow component of stormflow events. In view of the limited number of pre-cyclone stormflow samples, stormflow exports were calculated by simply multiplying total stormflow volume with the average stormflow concentrations given in Table 13.13. This, of course, is a rather crude method, and the stormflow exports may therefore be more or less seriously in error. The resulting annual exports of nutrients in baseflow, stormflow and total streamflow are presented in Table 13.14. Exports in baseflow were generally larger than in stormflow, with the exception of those for K and NO_3. Due to the low concentrations, nutrient exports were fairly low when compared with losses from other tropical catchments. Because the total export is a composite of the exports in base- and stormflow, any errors in the latter (N, P and K) tend to produce (relatively small) changes in the nutrient export these important nutrients. Bruijnzeel

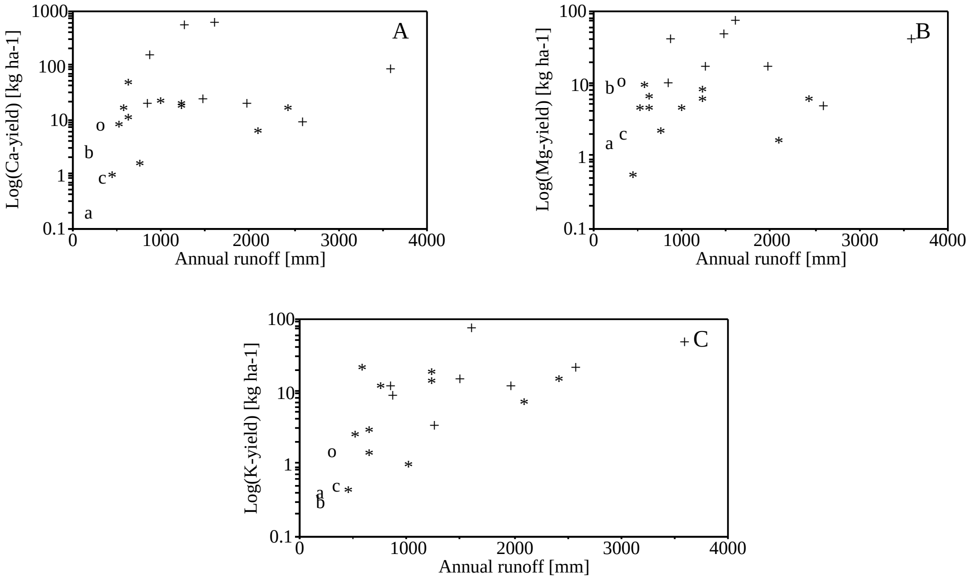


Figure 13.3: *Scatter plots of annual runoff* versus *yields of Ca (A), Mg (B) and K (C) for tropical forest ecosystems differentiated according to soil type (*: oxisols/ultisols; +: mollisols/vertisols) or location (a: Tulasewa; b: Korokula; c: Koromani; o: Oleolega). After Bruijnzeel (1990) and Malmer (1993).*

(1990; Table 3) reviewed the annual water yield and corresponding nutrient export data from a number of studies in tropical forests and grouped them according to their soil type and elevation (lowland/montane).

The nutrient exports in streamflow from the Oleolega catchment were larger than those calculated from soil moisture samples and drainage from the forest plots. This could only partly be due to differences in drainage totals and parent rock. The high exports of Na, Mg, Ca and Si from the catchment, compared to those from the forest plots (Table 13.11), suggest that these elements may well have been underestimated in the latter case due to the impossibility to sample moisture within or below the zone of active weathering (*cf.* Eernisse, 1993).

Additional data for lowland tropical rain forest was obtained by Malmer (1993) in Sabah, Malaysia. The annual nutrient exports obtained from the catchment and forest plots presently studied has been plotted in Figure 13.3 together with the lowland data (excluding spodosols and inceptisols) obtained by Bruijnzeel (1990) and Malmer (1993). The annual runoff values from the study sites in SW Viti Levu fall are lower than those obtained in the studies reviewed by Bruijnzeel (1990) and that of Malmer (1993), and the relatively low annual yields of Ca and K confirm the observed decreasing trend of the yield of these nutrients with annual runoff. However, annual yields of Mg at our study sites were relatively high in view of the low annual runoff.

Table 13.15: *Average post-cyclone concentrations and standard deviations (SD) of baseflow samples (n= 11) collected in the forested Oleolega catchment (between December 2, 1990, and January 7, 1991), as well as for baseflow samples collected in the grassland Ividamu catchment (January – September, 1991; n= 10). Levels of significance (*Student's t*) for differences between means of pre- and post-cyclone compositions added for comparison.*

Location	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Oleolega pine forest (1)																		
Mean	94	6.65	11.23	0.89	4.35	3.04	0.21	7.05	38.72	5.94	0.15	0.02	13.8	0.10	0.35	0.14	0.15	0.02
SD	4	0.06	0.23	0.39	0.14	0.12	0.13	1.40	2.34	1.02	0.19	0.01	0.3	0.03	0.10	0.03	0.13	0.00
Ividamu grassland (2)																		
Mean	179	6.67	15.14	0.58	9.24	9.92	0.23	13.37	97.83	1.74	0.06	0.12	12.0	0.07	3.51	1.41	0.19	0.05
SD	33	0.13	1.19	0.58	1.65	1.94	0.10	1.26	22.92	0.84	0.02	0.16	1.4	0.03	4.51	0.85	0.20	0.06
Comparison between pre- (A) and post-cyclone (B) baseflow concentrations																		
(1) A <> B	<***	ns	<***	<***	<***	<***	ns	<***	<***	>***	ns	ns	ns	<***	ns	>***	<**	ns
(2) A <> B	<**	<***	ns	ns	<***	<***	<*	ns	<***	ns	>**	ns	<**	ns	ns	<*	ns	ns

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

13.8 Impact of Cyclone Sina on the Baseflow Composition

The impact of cyclone Sina on the chemical composition of baseflow was evaluated from 11 samples collected between December 2, 1990 and January 7, 1991. Logging of cyclone damaged trees had started in the catchment in December, but less than 10% of the catchment area had been logged at the beginning of January. As such the effect of harvesting on baseflow composition could be considered negligible and any differences between the pre- and post-cyclone baseflow composition could be attributed to the cyclone event. The average post-cyclone baseflow composition is shown in Table 13.15. Because the discharges at which the baseflow samples were collected were not significantly different for the pre- and post-cyclone periods, the observed changes may be due entirely to cyclone effects. As would be expected from the deposition of sea spray and the transfer of large amounts of debris by the cyclone, concentrations of most constituents increased significantly after the event. However, the mean concentration of SO_4 in post-cyclone baseflow was significantly lower than the pre-cyclone average. This is consistent with the relatively low contribution of SO_4 in cyclone rain water (Cl/SO_4= 7.1) compared to pre-cyclone rain water (Cl/SO_4= 1.4; Table 13.3). Mn concentrations decreased as well after the cyclone event. The significant increase of Al reflects a change in the detection limit from 0.05 mg l^{-1} to 0.10 mg l^{-1}, rather than a real change since this element fell below the detection limits for both periods.

Asbury and Scatena (pers. comm.) also observed increased concentrations of K, Ca, and Mg in streamflow from a small watershed in the Bisley area in Puerto Rico after the above-ground biomass of the natural rain forest had been reduced by 50% (Scatena *et al.*, 1993) during the passage of hurricane Hugo in 1989.

Post-cyclone concentrations of Mg, Ca, HCO_3 in the baseflow from the grassland Ividamu catchment were significantly higher than corresponding pre-cyclone values (Table 13.15) but, unlike those in the forested Oleolega catchment, pre- and post-cyclone concentrations of Na, K, Cl and SO_4 were not significantly different, which may reflect differences in the trapping efficiency for cyclone sea spray between grass and pine forest. A possible explanation for the increased post-cyclone concentrations of Ca and Mg may be that cyclone depositions of Na and K were exchanged against Ca and Mg in the soil, which were subsequently leached at a higher rate. The grassland biomass in November 1990 (dead grass) was not likely to be affected much by the cyclone and observed differences in pre- and post-cyclone NO_3 and NO_4 concentrations, and possibly also in pH values, may reflect seasonal variations.

Since there had been little rainfall in the period between cyclone Sina and the start of harvesting, the effect of the cyclone on the chemical composition of stormflow could not be studied. The effects of harvesting and subsequent burning on baseflow and stormflow chemistry will be discussed in Chapter 15, although some of the changes reported therein must be attributed to the impact of the cyclone.

Chapter 14

Summary of Forest Nutrient Cycles

14.1 Introduction

From the nutrient point of view, the sustainability of plantation forestry depends on whether the nutrient losses associated with harvesting at the end of a rotation, as well as with site preparation (burning of slash) and plantation establishment (enhanced leaching), can be minimized in such a way that the soil remains capable of providing the required nutrients for uptake in subsequent rotations (Bruijnzeel, 1992b). One of the goals of the present study was to quantify these requirements for a chronosequence of pine forests, so as to provide information on whether future rotations in SW Viti Levu were likely to suffer from nutrient deficiencies. Plantation nutrient requirements change with the age of the forest, and may be approximated by studying an age series of sites as a substitute for a long-term study in a single forest (Hase and Fölster, 1982). The transfer of nutrients from the soil into the biomass at the various stages of forest development may be evaluated from nutrient budgets, provided that all other components of the budget are known.

The nutrient contents of the various compartments of the ecosystem (vegetation, litter layer, soil) and amounts of nutrients cycling through the ecosystem in water (precipitation, throughfall and stemflow, litter percolate and soil moisture) and litterfall have been quantified in the previous chapters. Nutrient budgets can now be compiled for the forest chronosequence to identify the period of maximum uptake as well as to quantify the uptake of nutrients from soil reserves. As indicated earlier, differences existed between soil chemical and physical properties at the various sites, which made a direct comparison difficult for some nutrients (*e.g.* K; *cf.* Section 4.4).

Although it is recognised that mineral weathering also constitutes an important input of nutrients for these deep-rooted pine forests, it is not possible at this stage to quantify contributions by mineral weathering. This will be done in Chapter 16 which discusses the overall nutrient budget for a *Pinus caribaea* plantation throughout a rotation period. Furthermore, estimates for the amounts of nutrients transferred from the soil to the forest ecosystem in the study plots are presented in Section 14.2.1.

Nutrient losses associated with the removal of merchantable timber at the end of a rotation period, and those by increased leaching following harvesting and burning of the slash will be discussed separately in Chapter 15.

More or less complete nutrient budgets could only be calculated for the macronutrients, because micronutrients had not been analysed in the soil (Zn, Mn, B) and water samples (Zn, B). The budgets presented for N are obviously incomplete due to the exclusion of the gaseous phase and the effects of various biochemical processes on the cycling of this nutrient (including fixation by bacteria, denitrification during wet conditions *etc.*). No corrections were applied to the nutrient contents of the forests to account for differences in stocking, since a reduction in stocking with increasing forest age resulting from cyclone damage must be considered the norm in Fiji. However, pre-cyclone and post-cyclone nutrient budgets will be presented in the following sections to illustrate the impact of cyclone Sina.

14.2 Pre-cyclone Nutrient Cycling Patterns

14.2.1 Nutrient Input – Output Budgets at Ecosystem Level

Information on whether nutrients are accumulating or being lost at ecosystem level can be obtained by comparing inputs with outputs. The net annual nutrient gains or losses at the Tulasewa, Korokula and Koromani forest plots, as well as those at the forested Oleolega catchment were calculated as the difference between annual atmospheric inputs and the corresponding exports in water leaving the ecosystems either as drainage or streamflow (*cf.* Chapter 13). Effects of cyclone Sina were excluded by using pre-cyclone concentrations in rainfall and drainage (Tables 13.4, 13.11 and 13.14). Data for Korokula and Koromani forests were collected during an 11-month period in 1990 and were linearly extrapolated on a time basis to obtain annual estimates. The results are presented in Table 14.1.

Inputs of N were calculated as the sum of N-NH_4 and N-NO_3 inputs in bulk precipitation, whereas that of P was taken equal to that of P-PO_4 only, as total N and total P had not been analysed in rain water samples collected before July 1990. However, the sum of N-NH_4 and N-NO_3 concentrations was often higher than the concentration of total N in rainfall and because both PO_4 and total P in subsequent samples were below the respective detection limits the results will not have been influenced much by this practice.

The atmospheric nutrient inputs for the forests in Fiji were rather low compared to those observed in various tropical countries elsewhere (Bruijnzeel, 1989a, 1991), which is in accordance with the absence of sources of polution and the rather low annual rainfall in the region. The high inputs of K at Tulasewa forest, and of P at the Oleolega catchment, are somewhat suspect and may be due to analytical errors as K and P inputs at the surrounding sites were consistently lower (Table 13.3).

Annual nutrient losses by leaching from the forest plots were also low, which may partly be due to the high water use of the forests which tends to restrict the occurrence of drainage to relatively short periods after heavy rainfall. Furthermore, uptake of nutrients from the soil solution by the rapidly growing pines may have reduced the nutrient concentrations in water percolating through the rooting zone, in which the water samples were collected, and on which the calculations of exported nutrients were based. Somewhat larger exports of nutrients released by weathering would be expected in water percolating through the weathering zone, as suggested by the exports of Ca,

Table 14.1: *Atmospheric nutrient inputs (based on actual precipitation amounts), outputs with drainage, and net gains or losses cyclones in pine plantations at various stages of development. Weathering inputs and in- and outputs associated with cyclone Sina not included.*

Location	Age	N	P	K	Ca	Mg	Mn	Zn	B
Annual Atmospheric Input [kg ha-1], Pre-cyclone 1990									
Tulasewa Forest	6	<4.2	<0.09	<6.1	<2.3	<1.1	<0.30		
Korokula Forest	11	<3.5	<0.07	<1.9	<1.4	<1.1	<0.30		
Koromani Forest	15	<2.5	<0.08	<1.8	<1.5	<1.2	<0.30		
Oleolega Catchment	15	<4.0	<0.55	<2.2	<2.1	<1.3	<0.84		
Annual Output with Drainage or Streamflow [kg ha-1], Pre-cyclone 1990									
Tulasewa Forest	6	<0.2	<0.01	0.4	0.2	1.5	<0.10		
Korokula Forest	11	0.8	0.02	0.4	2.8	9.8	<0.10		
Koromani Forest	15	0.8	<0.01	0.6	1.0	2.3	<0.20		
Oleolega Catchment	15	<0.3	<0.06	1.5	8.2	11.2	0.49		
Net Annual Gains (+) or Losses (-) [kg ha-1], Pre-cyclone 1990									
Tulasewa Forest	6	4.0	0.08	<5.7	<2.1	<-0.4	0.20		
Korokula Forest	11	<2.7	<0.05	<1.5	<-1.4	<-8.7	0.20		
Koromani Forest	15	<1.5	0.07	<1.2	<0.5	<-1.1	0.10		
Oleolega Catchment	15	3.7	0.49	<0.7	<-6.1	<-9.9	<0.35		

Mg and Mn in streamflow from the Oleolega catchment (*cf.* Table 14.1).

Comparison of the overall annual inputs and outputs suggested that N, P, K and Mn accumulated at all sites, although at (very) low rates. However, this conclusion must be looked upon with caution as the nutrient concentrations in both rain water and water leaving the sites were close to, or below, the detection limits. Losses of Mg were observed at all sites, whereas Ca was lost from the Korokula forest plot and the Oleolega catchment, but accumulated in the Tulasewa and Koromani forest plots. Because pine roots penetrated the zone of active weathering in all sites, with the possible exception of Koromani, these losses of Mg, and to a lesser extent of Ca, suggest that these elements were released by weathering in excess of amounts taken up by the vegetation (see also Chapter 16).

In spite of the different techniques used to obtain estimates of the nutrient exports from the respective sites, nutrient gains and losses from the catchment compared reasonably well with those from the forest plots (Sections 13.7.1 and 13.7.2), lending confidence to the results.

14.2.2 Intra-System Nutrient Cycling

Nutrients cycle continuously within the ecosystem and this cycle has been called the intra-system cycle (*cf.* Figure 1.2, Likens *et al.*, 1977). The various components of the intra-system cycle for the forest chronosequence under study have been quantified in Table 14.2. The net annual uptake by the vegetation (*sensu* Gholz *et al.*, 1985) was calculated as the sum of nutrients accumulating in the above-ground living pine biomass, and those returned to the forest floor in pine litterfall and canopy wash. The canopy wash may have contained some nutrients leached from the undergrowth

Table 14.2: *Quantification of the components of the intra-system nutrient cycle of Pinus caribaea at various ages and various indices of 'nutrient use efficiency'.*

Location	Age	N	P	K	Ca	Mg	Mn	Zn	B
Annual Accumulation in Pine Biomass [kg ha-1], Pre-cyclone 1990									
Tulasewa Forest	6	35.1	4.8	22.4	18.4	8.8	1.70	0.24	0.03
Korokula Forest	11	9.2	1.8	4.2	5.8	3.1	0.45	0.08	0.01
Koromani Forest	15	10.8	1.2	6.6	8.5	2.7	0.65	0.10	0.01
Annual Returns in Throughfall and Stemflow [kg ha-1], Pre-cyclone 1990									
Tulasewa Forest	6	0.9	0.0	9.9	0.4	1.5	-0.10		
Korokula Forest	11	-0.6	0.1	11.0	1.8	3.6	-0.10		
Koromani Forest	15	0.2	0.1	16.8	2.0	2.5	-0.10		
Annual Returns in Pine Litter Fall [kg ha-1], Pre-cyclone 1990 #									
Tulasewa Forest	6	19.0	0.8	4.6	43.1	9.7	2.50	0.12	0.04
Korokula Forest	11	34.2	1.9	8.9	56.9	24.7	3.70	0.19	0.06
Koromani Forest	15	20.6	0.9	5.5	33.1	10.4	1.90	0.08	0.03
Net Annual Uptake by Pines [kg ha-1], Pre-cyclone 1990									
Tulasewa Forest	6	55.0	5.6	36.9	61.9	20.0	4.10	>0.36	>0.07
Korokula Forest	11	42.8	3.8	24.1	64.5	31.4	4.05	>0.27	>0.07
Koromani Forest	15	31.6	2.2	28.9	43.6	15.6	2.45	>0.18	>0.04
Fraction of Net Annual Uptake Provided by Internal Cycling [%]									
Tulasewa Forest	*6*	*36*	*14*	*39*	*70*	*56*	*59*	*>33*	*>55*
Korokula Forest	*11*	*79*	*53*	*83*	*91*	*90*	*89*	*>70*	*>83*
Koromani Forest	*15*	*66*	*45*	*77*	*81*	*83*	*73*	*>44*	*>68*
Ratio of Net Primary Production to Net Annual Uptake by Pines									
Tulasewa Forest	*6*	*500*	*4930*	*745*	*444*	*1375*	*6709*	*76408*	*392957*
Korokula Forest	*11*	*394*	*4435*	*699*	*261*	*537*	*6796*	*62419*	*234069*
Koromani Forest	*15*	*473*	*6797*	*517*	*343*	*959*	*11234*	*83072*	*339841*
Ratio of Annual Litter Fall Mass to Nutrient Returns to the Forest Floor									
Tulasewa Forest	*6*	*264*	*6426*	*1090*	*116*	*517*	*2005*	*41767*	*125300*
Korokula Forest	*11*	*271*	*4886*	*1043*	*163*	*376*	*2509*	*48863*	*154733*
Koromani Forest	*15*	*260*	*5957*	*975*	*162*	*515*	*2822*	*67013*	*178700*
Annual Accumulation in Litter Layer [kg ha-1], Pre-cyclone 1990									
All sites	0-15	2.5	0.1	0.3	4.4	1.4	0.20	0.00	0.01
Mean Annual Release (+) or Uptake (-) by the Undergrowth Vegetation [kg ha-1]									
Tulasewa Forest+	0-6	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00
Korokula Forest+	6-11	6.2	0.6	17.7	3.0	3.2	0.37	0.02	0.01
Koromani Forest+	11-15	-2.0	-0.2	-5.7	-1.0	-1.0	-0.12	-0.01	-0.00
Net Annual Uptake (+) or Return of Soil Nutrients [kg ha-1], Pre-cyclone 1990*									
Tulasewa Forest	6	33.6	4.8	17.0	20.7	10.6	1.70	0.24	0.04
Korokula Forest	11	3.0	1.3	-14.6	8.6	10.0	0.08	0.06	0.01
Koromani Forest	15	13.8	1.4	11.4	13.3	6.2	0.87	0.11	0.02

#: Trace elements for foliage only; *: Annual gains or losses assumed zero for Zn and B
+: Obtained from the mean annual decrease in undergrowth mass, using nutrient concentrations in grass

vegetation, and this may have led to a slight overestimation of the computed net annual uptake by the pines. The mean annual release of nutrients as a result of changes in the undergrowth biomass was calculated from the difference in the nutrient content of the undergrowth vegetation (Tables 11.14 – 11.16) from one age class to the next, divided by the number of years between observations. Although the composition of the undergrowth vegetation changed during the course of a rotation, its nutrient content had to be calculated using nutrient concentrations obtained for grassland vegetation. As such the estimates for the older forests may contain relatively large errors.

The annual production rates of foliage and woody tissue were high in the young Tulasewa forest, which therefore accumulated nutrients at a high rate (Table 14.2). The canopy was fully developed at age 11, represented by Korokula forest, and from then on nutrient accumulation occurred mainly in the form of nutrient-poor woody tissue and at a much lower rate. Biomass production was some 20% lower in the Korokula forest plot than that in the Koromani forest plot (Table 11.7), resulting in slightly lower accumulation rates for N, K, Ca, Mn, Zn and B, but not for P and Mg. The higher P and Mg accumulation in the pine biomass of the former may be attributed to higher nutrient concentrations in plant material (Table 11.11), possibly as a result of differences in available Mg and P between the two soils (Section 11.5.3).

The annual return of nutrients to the forest floor occurred predominantly in litterfall, with contributions by throughfall and stemflow amounting to less than 20% of the total for Mg, and less than 5% for N, P, Ca and Mn at all sites. However, the larger part of K was returned to the forest floor in throughfall and stemflow, contributing 55%, 68% and 73% to the total in the Tulasewa, Korokula and Koromani forest plots, respectively. Nutrients returned in throughfall and stemflow are mainly in ionic form and are therefore directly available for uptake by plants, whereas those in litterfall become available only slowly during decomposition of the litter. The cycling of K through the ecosystem must therefore be considered much more rapid than those of the other nutrients. This holds both for natural and plantation forests in the tropics (Bruijnzeel, 1983a; Parker, 1983; Vitousek and Sanford, 1986; Burghouts, 1993). Litter production was considerably higher in the Korokula forest plot than in the Tulasewa and Koromani plots, which resulted in high annual nutrient returns at the former site. The difference in litter production between Korokula forest on the one hand, and Koromani and Tulasewa forests on the other hand must be attributed to differences in the soils (particularly soil depth, texture and water holding capacity, *cf.* Sections 4.3 and 6.5).

The net annual uptake of nutrients was largest early in the rotation period due to the high accumulation rate in the pine biomass, but generally decreased with forest age after age 6. The high net uptakes of Ca and Mg in Korokula forest should be attributed to the high rate of litter production, rather than to accumulation in pine biomass. Internal cycling constituted between 13% (P) and 63% (Ca) of the net annual uptake in Tulasewa forest. Higher proportions were found in the older forests, with values ranging between 51% (P) and 86% (Mg) in Korokula forest, and 43% (P) and 76% (K) in Koromani forest. The relative amounts of P in internal cycling were much lower than those of the other nutrients at all sites. This suggests that P is strongly retained within the biomass, possibly through retranslocation before abscission of old foliage. The relatively low percentages for N indicate that retranslocation may be important for this nutrient as well (*cf.* Vitousek, 1984). This contention was supported by the higher concentrations of N and P in fresh needles compared to those in needle fall (see Tables 11.8–11.10 and 12.2).

The 'nutrient use efficiency' of a forest ecosystem may be evaluated using the ratio of the net primary production (NPP, taken as the sum of the CAI of biomass and the annual litter production) to the net annual uptake (Vitousek, 1982; Gholz *et al.*, 1985). Alternatively, the ratio of litterfall mass to the nutrient returns to the forest floor in litterfall and canopy wash may be used (Vitousek, 1984). Both indices were calculated for Tulasewa, Korokula and Koromani forests and have been included in Table 14.2. Vitousek (1982) examined the relationship between 'nutrient use efficiency' and nutrient cycling for a wide range of forests and observed that the 'nutrient use efficiency' of forests on nutrient-poor soils was higher than on nutrient-rich sites. Comparison of the indices published by Vitousek (1984) for N, P and Ca in 62 natural tropical forests older than 25 years with those presently obtained indicated that the pine plantations in Fiji were very efficient in their use of N and P, exceeding the range for N (50-180) and with values near the upper range for P (1000–7500). The nutrient use efficiency of Ca was low (Tulasewa) to normal. Gholz *et al.* (1985) presented ratios of NPP to net annual nutrient uptake of N, P, K, Ca and Mg for a chronosequence of slash pine plantation forests (2–34 years) on a nutrient-poor soil in Florida and found that the nutrient use of their stands was highly efficient for P and K, and to a lesser extent for N and Ca, whereas nutrient use efficiency increased greatly with the forest age. They attributed the high efficiency for P in the older forests to reductions in the availability of P in the soil, which forced the trees to retranslocate increasingly larger amounts of P in order to sustain growth. The indices for N, P, K, Ca and Mg for Tulasewa and Korokula forests, and those for N, P and Ca in Koromani forest, were considerably higher than those found by Gholz *et al.* (1985) in stands of corresponding age (5, 8 and 14 years old). In spite of the high 'nutrient use efficiencies', biomass production was high in the Fiji plantations and no evidence was found that growth was limited by the availability of nutrients in the soil at any stage.

Lugo (1992) compared the dynamics of *Pinus caribaea* (age 4 and 18.5 years) and mahogany plantation forests (age 17 and 49 years) with those of paired secondary forests of the same age on volcanic soils in Puerto Rico, and observed higher 'nutrient use efficiencies', particularly for P, for the plantation forests than for the paired secondary forests using the two indices discussed above. His NPP/Uptake ratios for P in the pine plantation forests were of similar magnitude (3677–4719) as those calculated for Tulasewa and Korokula forests. However, his ratios for N were lower (131–157), whereas his ratios for K were higher (950–839). Because the plantation forests were on the same soils as the paired secondary forests, Lugo (1992) concluded that the high nutrient use efficiency by the plantation forests for P was a characteristic of the species, rather than an indicator of the nutrient status of the soil. The higher 'nutrient use efficiency' of the plantation forests could be explained by the fact that in the plantations a greater proportion of the nutrients needed for sustained growth was derived from retranslocation than in the paired secondary forests (Lugo, 1992). The 'nutrient use efficiency' of N and P increased with forest age in the Puerto Rican plantation forests (Lugo, 1992), which suggested that the demands for nutrient uptake from the soil were likely to decrease since nutrients taken up earlier were increasingly retranslocated. This is supported by the data obtained during the present study. A decrease in the 'nutrient use efficiency' of K was observed in the Puerto Rican forests, as well as in the forests presently studied. This may be related to the fact that K is very mobile, and is being leached increasingly from the canopy as the forests grow older and increase their foliage biomass (Table 14.2).

The net annual uptake or return of soil nutrients (Table 14.2) was calculated as the difference between net gains and losses to and from the ecosystem (Table 14.1) and the respective uptake and returns by and from the vegetation and litter layer.

The demands on the soil were highest early in the rotation period and decreased sharply after canopy closure, when considerable amounts of nutrients (*e.g.* K, N, Mn) must have been released from the dissapearing undergrowth vegetation. The release of K from the undergrowth vegetation between age 6 and 11 exceeded uptake by the pine trees and the accumulation in the litter layer, resulting in a net input of K to the soil. The undergrowth biomass increased again after age 11 due to the more open character of the older, cyclone damaged, forest. Nutrient demands from the soil increased correspondingly, but remained much lower than those early in the rotation (Table 14.2).

Comparison of the nutrient demands of the vegetation with the nutrient reserves in the soils (Section 4.4) suggested that the pools of Ca and Mg were sufficiently large to sustain plantation forestry at all sites. Amounts of K available in the soils would also be sufficient, provided that nutrient losses associated with harvesting would be minimized. As some of the nitrogen may be obtained by the forest by fixation of gaseous N, deficiencies for this nutrient are also unlikely. As for P, the estimates of 'available' P obtained with the Ca-Lactate method were much lower than those obtained with the Bray II method. If the latter are taken as representative for the availability of P, no deficiencies would be expected in the Tulasewa and Korokula forest plots. However, Bray-II 'available' P was fairly low in Koromani forest (24 kg ha^{-1}), and deficiencies may be expected in the next rotation if losses of P during and after harvesting would not be minimized (see also Chapter 16).

Requirements of Na, K, Ca, and Mg the by forest in Tulasewa (and Korokula) could for the most part be supplied by weathering of the substrate as the base saturation of the soil remained above 85% throughout the profile, suggesting that no depletion occurred in spite of the high nutrient uptake by the trees.

14.3 Post-Cyclone Nutrient Cycling

The impact of cyclone Sina will be evaluated in this section by comparing post-cyclone nutrient budgets with the pre-cyclone budgets presented earlier for the Tulasewa, Korokula and Koromani forest plots. Because logging in the Oleolega catchment started soon after the event cyclone effects could not be separated from those as a result of harvesting, and input – output budgets for the Oleolega catchment will therefore be presented here separately. Atmospheric inputs at all forest plots during cyclone Sina and in the period following the event, the corresponding exports in water leaving the forests, and the net gains or losses are presented in Table 14.3. Data collected during the post-cyclone period (306 days) were extrapolated linearly on a time basis to obtain annual estimates. The influence of cyclone Sina on the inputs of N, P and Mn was negligible, because concentrations in cyclone rain water were close to (total N) or below (total P, Mn) the respective detection limits. The higher N inputs observed for the post-cyclone period, compared to those during the pre-cyclone period, reflected the higher concentrations of total N in rainfall during the former period (Table 13.3). Nutrient inputs of Mg, and to a lesser extent of K and Ca, reflected the deposition of sea spray by the cyclone. The errors in the estimates of the atmospheric nutrient inputs given in Table 14.3 may be considerable due to uncertainties in the amounts of nutrients deposited by cyclone Sina (see discussion in Section 13.4), which almost certainly must have been underestimated. The annual inputs presented for the post-cyclone period remained within the lower ranges of those presented by Vitousek and Sanford (1986) and Bruijnzeel (1989a, 1991).

Table 14.3: *Annual atmospheric nutrient inputs, corresponding outputs in water leaving the forests, and net gains or losses at the Tulasewa, Korokula and Koromani forest plots, including those resulting from the passage of cyclone Sina. Annual values obtained by linear extrapolation on a time basis.*

Location	Age	N	P	K	Ca	Mg	Mn	Zn	B
Annual Atmospheric Input [kg ha-1], Cyclone and Post-cyclone 1991									
Tulasewa Forest*	7	3.6	<0.5	<5.6	<1.8	<3.0	<0.4		
Korokula Forest	12	9.1	<0.2	<3.2	3.3	<4.3	<0.2		
Koromani Forest	16	5.2	<0.2	<4.2	<2.6	<5.4	<0.2		
Annual Export with Drainage [kg ha-1], Cyclone and Post-cyclone 1991									
Tulasewa Forest	7	<0.6	<0.2	2.0	<1.3	11.8	<0.2		
Korokula Forest	12	0.4	<0.1	0.6	6.9	39.1	<0.1		
Koromani Forest	16	0.4	<0.1	0.7	2.0	2.7	<0.1		
Net Annual Gains (+) or Losses (-) [kg ha-1], Cyclone and Post-cyclone 1991									
Tulasewa Forest	7	>3.0	0.3	<3.6	0.5	<-8.8	0.20		
Korokula Forest	12	8.7	0.1	<2.8	-3.6	<-33.8	0.10		
Koromani Forest	16	4.8	0.1	<3.5	<0.6	<2.7	0.10		

*: Cyclone rainfall inputs taken as 0.5 times those at Korokula Forest

Post-cyclone outputs of Mg, Ca and K in drainage, and possibly those of P (concentrations often below the detection limit), were larger than pre-cyclone outputs, whereas that of N was lower. However, outputs of N, P, K and Mn did not exceed the atmospheric inputs and small net annual gains were therefore observed for these nutrients at all sites. Small gains of Ca were calculated for Tulasewa and Koromani forest, whereas a small loss was derived for Korokula forest. In the year after the passage of cyclone Sina, Mg was exported from Korokula forest in much larger quantities than in the year before, which was due to increased concentrations of Mg in the soil moisture (Table 13.10). Larger exports of this nutrient were also observed at Tulasewa forest due to a combination of higher concentrations and increased drainage following the cyclone event. However, a small gain in Mg was observed at Koromani forest. A large proportion of the exchange places in the subsoils of Tulasewa and Korokula forests was occupied by Mg (Section 4.4) and some of these ions may have been exchanged against Na, which was deposited in large quantities on the soils by cyclone Sina. The CEC and base saturation of the soil in Koromani forest were much lower, and this may have prevented the release of Mg at this site.

In Puerto Rico, Asbury and Scatena (pers. comm.) also observed higher concentrations of nutrients in streamflow from the small Bisley catchments after hurricane Hugo reduced the above-ground biomass with 50% (Scatena *et al.*, 1993). However, since rainfall amounts were below average in the period following the event (Scatena and Larsen, 1991) no increase in the annual nutrient export was observed compared to the previous year.

The impact of cyclone Sina on the intra-system nutrient cycle was large as the cyclone downed more than 40%, 14% and 10% of the above-ground tree biomass in the Tulasewa, Korokula and Koromani forest plots, respectively. The damage to the nutrient-rich canopy was severe at all sites, leading to the transfer of large amounts of nutrients to the forest floor (Tables 12.10–12.12) and therefore eventually to the soil.

The post-cyclone sources, sinks and transfers of nutrients are presented in Table 14.4. The biomass of the forests immediately after the cyclone event was unknown, which made the calculation of the annual post-cyclone nutrient uptake by the vegetation from the biomass data difficult. Furthermore, uncertainties in the nutrient returns in cyclone litterfall, as well as in the accumulation of nutrients in the litter layer, were large due to the high spatial variation and the inability to include large wood in the samples (see Sections 12.3.3 and 12.5.3). Hence the following assumptions were made to obtain the estimates for post-cyclone nutrient uptake presented in Table 14.4:

- Post-cyclone diameter increments were only slightly lower than the pre-cyclone rates in the Tulasewa forest plot (Section 11.3.4) and post-cyclone annual nutrient uptake was therefore assumed equal to pre-cyclone uptake, multiplied by a correction factor to account for the reduction in stocking.
- Diameter increments in the Korokula and Koromani forest plots were zero during the nine months following the cyclone event, suggesting that nutrients taken up by the trees were exclusively used for the regeneration of foliage. Here the post-cyclone uptake was therefore approximated by the mean annnual pre-cyclone nutrient increment in branches, twigs and foliage, again after corrections were made for reductions in stocking.

Due to these and other uncertainties, the data presented in Table 14.4 may be relatively inaccurate. However, they may serve as a rough indication of the changes in the forest nutrient cycle after severe damage by a cyclone.

The cyclone transferred large amounts of nutrients from the canopy to the forest floor, the greater part of which were deposited as litterfall (Tables 12.4–12.6). The amounts of nutrients leached from the canopy and stem during cyclone Sina were presumably small, and the amounts in canopy and stem wash (Table 13.7) were probably overestimated as a consequence of the underestimation of atmospheric inputs during the cyclone event. The release of nutrients from the litter layer by decomposition is a slow process, and a large proportion of the nutrients deposited on the forest floor in litterfall remained immobilised in the litter layer, which resulted in a large accumulation of nutrients in the litter layer in the year following the cyclone event. The values presented in Table 14.4 represent only 8 months of post-cyclone data, and the actual accumulation rates will have been somewhat lower due to continued decomposition between August and November 1991, for which no data were available.

The 'nutrient use efficiency' of the forests for the post-cyclone period was evaluated using the litterfall – nutrient return index (Vitousek, 1984). Comparison of post-cyclone ratios with pre-cyclones ratios showed that the 'nutrient use efficiency' decreased considerably after the cyclone for P, K and Mg, with smaller decreases for the other nutrients at most of the forest sites. The low post-cyclone nutrient use efficiency could be attributed to less efficient retranslocation of nutrients in the cyclone damaged canopy before abscission of the foliage. This resulted in relatively high nutrient concentrations in post-cyclone litterfall compared to those in the pre-cyclone period, until several months after the cyclone event (Section 12.3.2).

The damage afflicted to the forests by cyclone Sina resulted in an enrichment of most soil nutrients a year after the event (Table 14.3) as indicated by higher nutrient concentrations in the soil moisture (see Section 13.6). Net returns to the soil were high for K and Ca, a large part of which were presumably retained in the soil on cation exchange places as the large inputs did not result in similar losses via drainage (Tables 14.3 and 14.4). Small net losses were observed for Mg in Tulasewa and Korokula forests due to increased outputs of Mg in drainage, but not in Koromani forest. Rain-

Table 14.4: *Quantification of the components of the intra-system nutrient cycle in the year following the passage of cyclone Sina. Note that the estimates for nutrient accumulation in the litter layer pertain to an 8-month period.*

Location	Age	N	P	K	Ca	Mg	Mn	Zn	B
Return in Cyclone Throughfall and Stemflow [kg ha-1]									
Tulasewa Forest+	7	-0.1	0.0	3.3	7.3	2.9	0.06		
Korokula Forest	12	-0.2	0.0	6.6	14.5	5.8	0.12		
Koromani Forest*	16	-0.2	0.0	6.6	14.5	5.8	0.12		
Return in Cyclone Litter fall [kg ha-1] #									
Tulasewa Forest	7	75.8	9.0	47.3	66.3	22.4	3.35	0.17	0.05
Korokula Forest	12	108.6	7.5	35.1	71.7	38.7	3.73	0.15	0.15
Koromani Forest	16	91.2	6.5	32.0	71.3	23.1	4.29	0.15	0.08
Accumulation in Pine Biomass [kg ha-1], Post-cyclone 1991*									
Tulasewa Forest	7	20.9	2.9	13.3	11.0	5.2	1.01	0.14	0.02
Korokula Forest	12	12.6	1.0	4.8	4.2	3.6	0.21	0.03	0.01
Koromani Forest	16	9.1	0.7	5.8	4.0	1.6	0.33	0.02	0.01
Return in Throughfall and Stemflow [kg ha-1], Post-cyclone 1991									
Tulasewa Forest	7	-1.7	0.0	11.2	1.2	1.2	-0.04		
Korokula Forest	12	-7.7	0.0	5.6	1.4	1.9	-0.02		
Koromani Forest	16	-3.4	0.0	7.1	1.4	1.4	-0.02		
Return in Litter Fall [kg ha-1], Post-cyclone 1991 #									
Tulasewa Forest	7	15.6	1.2	3.8	29.4	8.0	2.31	0.11	0.04
Korokula Forest	12	20.1	3.8	3.6	26.5	13.2	1.44	0.08	0.05
Koromani Forest	16	19.9	0.8	4.1	23.9	6.8	2.63	0.09	0.04
Net Annual Uptake by Pines [kg ha-1], Post-cyclone 1991									
Tulasewa Forest	7	34.8	4.1	28.3	41.5	14.4	3.28	0.25	0.06
Korokula Forest	12	25.0	4.8	14.0	32.1	18.7	1.63	0.11	0.07
Koromani Forest	16	25.6	1.5	17.0	29.3	9.8	2.94	0.11	0.05
Ratio of Annual Post-cyclone Litter Fall Mass to Nutrient Returns to the Forest Floor									
Tulasewa Forest	*7*	*259*	*2909*	*241*	*118*	*393*	*1587*	*33491*	*99953*
Korokula Forest	*12*	*325*	*1066*	*439*	*144*	*267*	*2841*	*50524*	*73809*
Koromani Forest	*16*	*227*	*4417*	*335*	*149*	*457*	*1440*	*42533*	*92791*
Accumulation in Litter Layer [kg ha-1], Cyclone and Post-cyclone period, Nov ’90 - Aug ’91									
Tulasewa Forest	7	62.2	5.3	13.5	43.3	12.2	1.99	0.07	0.02
Korokula Forest	12	66.4	3.1	8.3	20.5	12.7	0.89	0.11	-0.01
Koromani Forest	16	82.4	5.2	8.9	28.8	14.2	0.16	0.04	0.00
Net Annual Uptake (+) or Return (-) of Soil Nutrients [kg ha-1] in the year after the passage of Cyclone Sina @									
Tulasewa Forest	7	4.4	-1.1	-27.4	-19.8	1.0	-0.61	0.04	-0.01
Korokula Forest	12	-38.1	-3.5	-31.4	-57.9	5.6	-2.85	-0.01	-0.15
Koromani Forest	16	-4.3	-0.7	-27.4	-53.6	-15.7	-4.02	-0.09	-0.07

+: Cyclone canopy wash assumed 0.5 times that at Korokula forest
*: Cyclone canopy wash taken equal to that at Korokula forest
#: Trace elements totals for foliage only; @: Totals of Zn and B in moisture fluxes assumed zero

fall amounts during the post-cyclone period (Table 6.9) at the Korokula and Koromani plots were 7–10% lower than the corresponding long-term average for Nabou station (Table 6.2), which will have limited nutrient losses via drainage to some extent at these sites compared to those that would have occurred with more representative rainfall conditions. The converse was true for nutrient losses via drainage at the Tulasewa site, where post-cyclone rainfall was 42% higher than the corresponding long-term average.

The nutrient enrichment of the soil one year after the cyclone event, in combination with the further release of nutrients accumulated in the litter layer, seems sufficient to balance the forest nutrient uptake for at least another year. As such the effect of a major cyclone on the intra-system nutrient cycle may last several years, depending on the amount of damage afflicted to the forest (decrease in stocking) and the rate of decomposition of the cyclone debris.

Such disruptions of the intra-system nutrient cycles as a result of severe wind damage to natural rain forests were also observed in Puerto Rico after hurricane Hugo transferred large amounts of nutrients from the forest canopy to the soil surface (Lodge *et al.*, 1991; Steudler *et al.*, 1991; Scatena *et al*, 1993).

Part IV

Impact of Harvesting and Burning

Chapter 15

The Oleolega Catchment Experiment

15.1 Background Information

15.1.1 Introduction

The third phase in plantation forestry involves the harvesting of the timber and the site preparation for the next rotation. During this phase landings, landing access roads and skid tracks are constructed, the forest is felled and merchantable timber is extracted, often with the help of heavy machinery. This is usually followed by burning of slash, undergrowth vegetation and litter to prepare the site for replanting. All these practices change the water and nutrient cycles, and in places leave the soil vulnerable to physical and chemical deterioration by compaction, erosion and enhanced leaching of nutrients (Bruijnzeel, 1990; Anderson and Spencer, 1991).

No information was available in this respect for the plantation forests in Fiji, and only very little for pine vegetation on grasslands elsewhere in the tropics (Hudson *et al.*, 1983a,b). Hence the Oleolega catchment experiment was conducted with the following objectives:

- to quantify changes in the water cycle as a result of forest felling and burning of slash
- to quantify the impacts of timber harvesting and subsequent burning of the slash on the nutrient content of the vegetation – litter layer complex
- to study the impact mechanized timber harvesting on soil physical and chemical properties
- to provide information on changes in soil and stream water quality, and to quantify losses of nutrients in streamflow associated with harvesting and burning

This information of course is vital for forest managers as it enables the identification of critical management practices and associated nutrient losses, and helps to evaluate the sustainability of the plantation forests from the nutrient point of view.

Studies on the impacts of harvesting and burning of first rotation forest planted on fire-climax tropical grassland on the availability of nutrients for a second rotation are as yet non-existent. However, a number of studies have been published describing changes in soil properties following the conversion of natural rainforest to plantation forest (*e.g.* Cornforth, 1970; Lundgren, 1978; Chijioke, 1980; Hase and Fölster, 1983; Russell, 1983; Bruijnzeel, 1992b). Furthermore, comprehensive reviews of the literature on effects of disturbance of tropical rain forest ecosystems on carbon, nutrient and water cycles have been published by Bruijnzeel (1990) and Anderson and Spencer (1991). Although these studies pertain to natural forests, of which the biomass and nutrient content are much higher than those of pine plantation forests, some clues are provided as to what changes in soil chemistry, as well as water and nutrient cycles are likely to occur as a result of timber removal and burning of slash of the first rotation.

Forest clearance and subsequent burning usually results in an increase in soil bulk density, and a decrease in topsoil porosity and infiltration capacity. This is the result of soil disturbance and compaction, either by vehicles (Van der Weert and Lenselink, 1972; Lundgren, 1978; Kamaruzaman Jusoff, 1991; Malmer, 1993; Van der Plas and Bruijnzeel, 1993; Jetten, 1994) or by raindrop impact and increased losses of soil organic matter (as a consequence of higher soil temperatures and exposure to solar radiation) leading to structural degradation and erosion (Nye and Greenland, 1960; Lundgren, 1978; Lal, 1987; Anderson and Spencer, 1991). The extent to which physical soil properties are altered depends mainly on the type of equipment used for timber extraction and the volume of timber that is extracted. Manual extraction generally leads to low disturbance, whereas damage increases greatly when heavy machinery is used (Lal, 1987; Malmer and Grip, 1990; Bruijnzeel, 1992a), particularly if the soil is wet (Dias and Northcliff, 1985a,b; Kamaruzaman Jusoff, 1991)

Removal of the forest cover generally reduces the amounts of water lost by rainfall interception and transpiration, thereby increasing the annual water yield (Bosch and Hewlett, 1982), mostly through increased baseflow levels (Bruijnzeel, 1990; Malmer, 1993). However, in some instances shifts in the streamflow regime after deforestation, were such that reductions in the dry season flow were observed (Bruijnzeel, 1989b). Whether such a shift occurs seems to depend mainly on the intensity of the soil disturbance. Infiltration capacities of undisturbed forest soils are usually high, limiting the occurrence of overland flow and associated erosion, and allowing the replenishment of groundwater reservoirs during periods with high rainfall. Removal of the forest and the associated construction of impervious roads and landings leads to a reduction in catchment infiltration capacity, with the largest reductions on tracks, roads and landings (Bruijnzeel, 1992a). If basin infiltration capacity is reduced beyond a certain treshold value, overland flow may become widespread, thereby affecting the shape of the hydrograph (*e.g.* time to peak, magnitude of peak discharge) and thus increasing stormflow volume and limiting the percolation of water to groundwater reservoirs. Erosion as a result of overland flow may cause further degradation of the soil. The combined effect of changes in the hydrograph and high erosion rates may lead to flooding and sedimentation problems in downstream areas during periods of high rainfall, whereas the reduction in groundwater replenishment may lead to reduced flows during the dry season (Bruijnzeel, 1990). It follows that it is of utmost importance to minimize disturbance to the soil during harvesting, particularly in areas with steep topography, high rainfall intensities and a seasonal rainfall regime (Pearce and Hamilton, 1986).

Upon wood extraction substantial amounts of nutrients may be removed in harvested timber and even larger amounts are transferred from the nutrient-rich canopy to the forest floor in slash (Bruijnzeel, 1992a; Nykvist, 1992). For plantations established on grasslands, the amounts of nutrients stored in slash and litter after completion of a logging operation will be much higher than that stored in the initial grassland vegetation – litter complex, and burning results in the sudden release of a large proportion of these nutrients, which may easily be lost by volatilization during the burn (*e.g.* N, S; Little and Clock, 1985), or in water leaving the site as runoff or drainage to deep groundwater (*e.g.* K, Mg, Ca; Tiedemann *et al.*, 1979; Hudson *et al.*, 1983b). Therefore soil nutrients reserves may be reduced considerably after harvesting and burning compared to those present in the original grassland soils.

Cornforth (1970) observed reductions of 18–70% for total N, 0–67% for 'available' P and 13–81% for exchangeable K in acid sandy soils under 4–12 year old *Pinus caribaea* plantations in Trinidad compared to reserves in soils under nearby natural forest. Results for exchangeable Ca and Mg were less clear as reductions of up to 83% and 92%, as well as increases of up to 138% and 21% were observed, respectively. These nutrient losses were ascribed to erosion, but the possibility of leaching may not be excluded in this area of high rainfall (about 3000 mm year^{-1}; Cornforth, 1970).

Lundgren (1978) compared soils under natural forest with those underlying an age series of *Pinus patula* and *Cupressus lusitanica* plantations in upland Tanzania and observed that the soil organic matter and nitrogen contents increased during the first 4–8 years after establishment. This was followed by a decrease during periods of high nutrient uptake (age 15–20 years) and by an increase in older plantations (age above 30 years). Stocks of P and K, both in available and reserve forms, declined with plantation age whereas no clear trends were observed for Ca and Mg. Lundgren (1978) concluded that logging during the period of maximum productivity would have resulted in a deterioration of the soil fertility.

Chijioke (1980) studied the effects of the establishment of plantations in Nigeria and Brazil on soil physical and chemical properties and concluded that K deficiency could become a problem in future rotations of *Gmelina arborea* in Brazil, and to a lesser extent in Nigeria. No evidence was found that the removal of nutrients in harvested *Pinus caribaea* would create problems for future rotations, provided that soil disturbance during harvesting would be minimized and slash not be burned.

Russell (1983) compared the nutrient contents of ultisols under rain forest with those in recently logged and burned areas and with those under an 8.5 year old *Gmelina arborea* stand and a 9.5 year old *Pinus caribaea* forest in Jari Florestal, Brazil. The fertility of the soil was reported to have increased initially as a result of the harvesting and burning of the rain forest but it decreased in the course of the first rotation. The decrease in total nutrient stock was such that nutrient deficiencies (*e.g.* Mg, P, Ca) were predicted for the second or third pine rotations. It should be noted, however, that all of the above studies used the 'false time series' referred to earlier and the results should therefore be treated with caution.

Soil disturbance associated with the harvesting process was high in all these studies and considerable quantities of nutrients were eventually lost after the conversion of natural forest to plantation forest. Therefore some kind of nutrient deficiency was predicted to occur in future rotations, suggesting that sustained yields may not be possible with the current methods of logging and intensities of wood extraction and site preparation. The information given above also suggests that any soil physical or chemical improvement obtained during the active growth phase of the forest (*i.e.* phase two) may be offset by the disturbance of the soil and associated losses of nutrients during phase three.

The situation is slightly different in Fiji where the *Pinus caribaea* plantation forests have been planted on old grasslands without much disturbance to the soil during the first rotation. Furthermore, the soils are not too depleted, and roots were observed to penetrate into the zone of active weathering and even in cracks in the bedrock. As

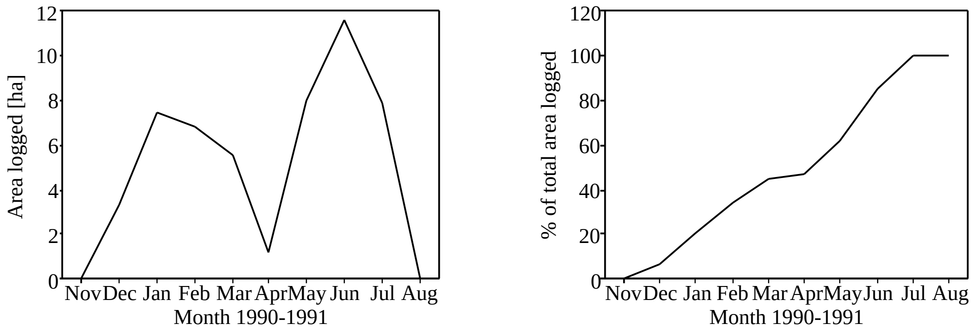


Figure 15.1: *Monthly totals of the area cleared from pines and the progress of harvesting expressed as a percentage of the total forested area in the Oleolega catchment.*

such the forests in Fiji may obtain some of their nutrient requirements directly from weathering of primary minerals. However, even under these relatively favourable conditions depletion of the soil nutrient reserves may eventually occur if the atmospheric nutrient input, the nutrient supply from weathering, the retention of nutrients that would otherwise have been removed during periodic grassland wildfires and the gain of nutrients from reductions in water yields during phase two are less than amounts removed by leaching, erosion, volatilization and in harvesting of merchantable timber during phase three.

The first 11 months of research in the Oleolega catchment were conducted when the catchment was completely under forest. Data on soil characteristics (Sections 4.3 and 4.4), water yield (Section 8.3) and water quality (Section 13.7.2) collected during this period were used as a baseline against which the impact of harvesting and subsequent burning of slash could be assessed. The impacts of cyclone Sina, harvesting and burning on, respectively, the vegetation, litter layer, soil, and water quantity and quality will be examined in the following sections, whereas a nutrient budget for a full rotation and an evaluation of the sustainability of the pine plantations in Fiji will be presented in Chapter 16.

15.1.2 Logging Procedures, Infrastructure and Site Preparation

Harvesting started in December 1990 at age 15.9 as a salvage operation after the forest had been severely damaged by cyclone Sina in November 1990 and continued until August, 1991. Absolute and cumulative monthly totals of logged areas, and the harvesting progress expressed as a percentage of the forested area (51.6 ha) are shown in Figure 15.1. Logging proceeded slowly during the wet season, partly due to adverse weather conditions (wet soils preventing wood extraction), and partly due to conflicts between the land owners and Fiji Pine Ltd. About 50% of the area had been logged in May 1991 whereas the remainder was removed much more quickly during the subsequent drier months.

Before harvesting the area taken up by frequently used and regularly maintained roads (for fire prevention) totalled 1.4 ha (2.2% of total area) with a total road length of 2.0 km. These were located on the ridges forming the southern and eastern catchment boundaries (Figure 3.4). The area of roads constructed for planting purposes in 1975, and infrequently used thereafter, amounted to 1.0 ha (1.6%) with a total length of 1.2 km. These roads were located on the ridges forming the western catchment boundary. At the time of the study some sections of this road (area 0.5 ha) were completely overgrown with grasses and young pine and *Casuarina* trees. The total area covered by roads prior to harvesting amounted to 2.4 ha, or 3.8% of the catchment area, with a total road length of 3.2 km. Before and shortly after harvesting started (December 1990, January 1991) existing roads were upgraded and landings and landing access roads constructed. To facilitate extraction additional road cuts were later constructed in poorly accessible areas (*e.g.* on steep slopes) using heavy earth moving machinery. An uphill logging technique was used in which skidders operated from tracks fanning out from the landings to retrieve trees felled downslope. The effect on the infrastructure of the catchment is visualized in Figure 15.2. By the end of July, 1991, road length had increased nearly threefold to 9.9 km, and the area covered by roads and landings had increased to 4.9 ha, whereas skidder tracks occupied another 1.2 ha. As such the topsoil in an area covering some 10% of the total catchment area was disturbed severely after completion of harvesting.

The slash, undergrowth vegetation and litter layer were burned in the evening of August 15, after harvesting had been completed by the end of July. The fire was ignited on the ridges and burning proceeded downwards until the fire reached the wet riparian zone where it stopped due to lack of dry fuel. The burn was done at night when low wind speeds minimized the risk of spreading of the fire to adjacent forested areas. The litter layer moisture content was measured on August 2 and amounted to 28($\pm$13)% of dry weight. No rainfall was recorded until August 15 and the low moisture content of the slash resulted in a high intensity burn.

The undergrowth vegetation returned within several months after the burn. In April 1992 a map of the vegetation density was compiled by Mr. T.T. Rawaqa from Fiji Pine Ltd. from visual observations. This showed that the vegetation had densities of 60–100% , 30–60% and 0–30% on 49%, 30% and 21% of the logged catchment area, respectively. The vegetation had not returned at all on the severely compacted surfaces of landings, roads, and tracks (T.T. Rawaqa, pers. comm.). Replanting of the catchment to pines commenced in January 1992. Second rotation pines were also planted on landings, roads and tracks and it will be interesting to see how the compaction of these surfaces will affect the growth of the crop.

15.1.3 Methods and Instrumentation

To study the effect of timber harvesting and subsequent burning on soil chemical properties, samples were collected in December 1990 when the catchment was under forest, and in September 1991 shortly after timber harvesting and burning of slash. A rectangular grid (100*100 m) was placed over a map of the catchment and on both occasions samples were collected at the 25 randomly chosen grid points shown in Figure 15.3. Sampling was done with an auger in a similar fashion as described for the forest plots (Section 4.2). Pre-harvesting samples were collected at depths of 0–10 cm, 10–20 cm and at one 10 cm depth interval between 30–60 cm, depending on the depth of the bedrock. Post-burning samples were collected at depths of 0–10 cm, 10–20 cm, 30–40 cm and, if possible, at 50–60 cm. Landings and tracks had been constructed during harvesting on nine sample points, and at these locations samples were collected at the initial sample point, as well as at a point in the vicinity where

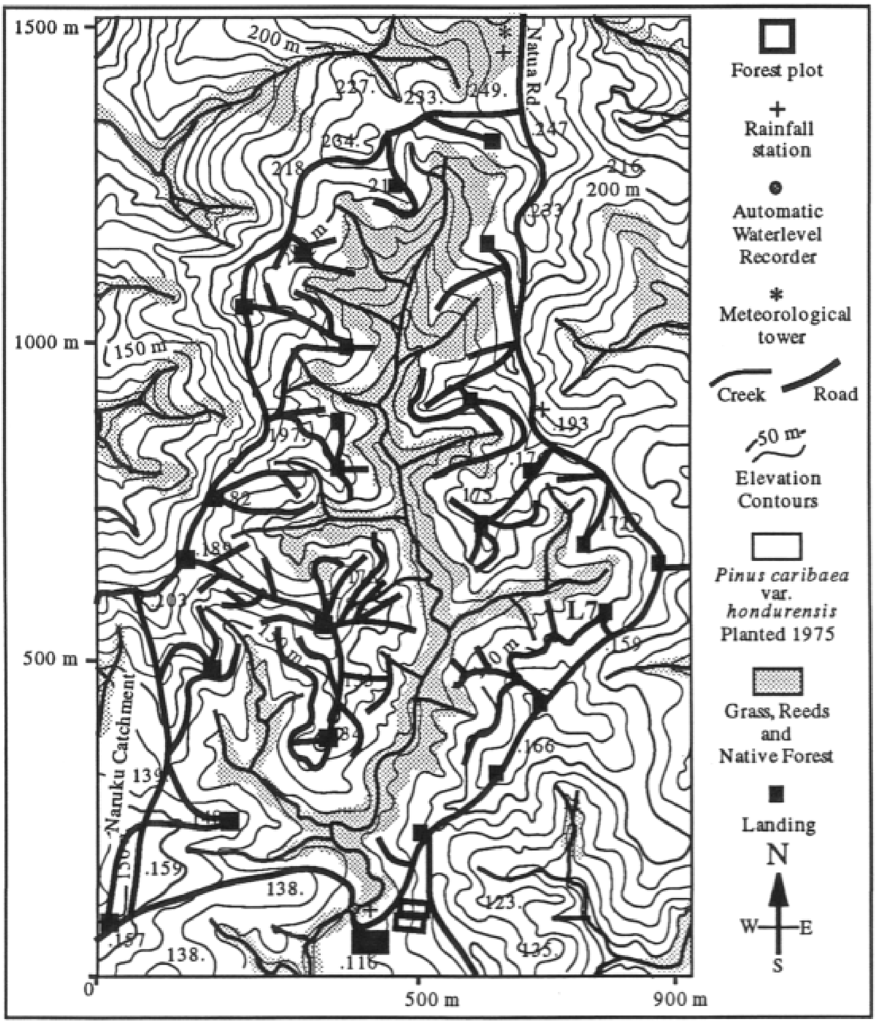


Figure 15.2: *Network of roads, landings and skidder tracks after the completion of harvesting in the Oleolega catchment.*

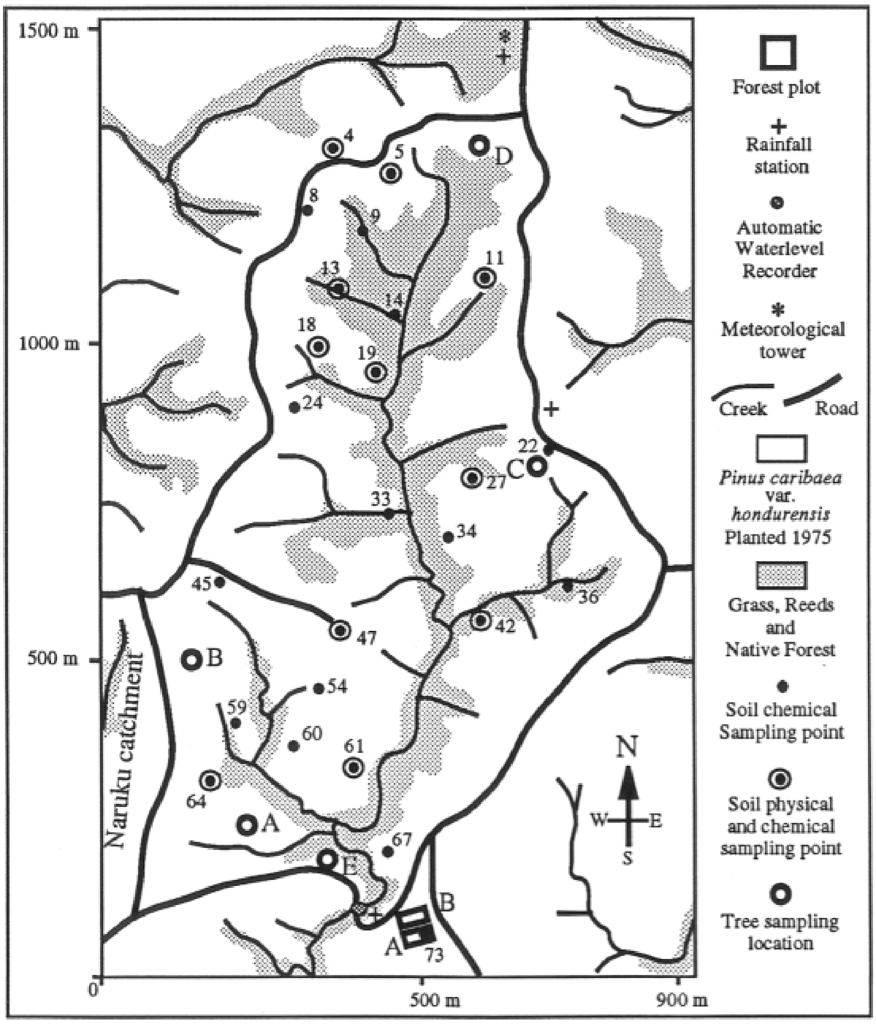


Figure 15.3: *Map of the Oleolega catchment showing the locations of soil, litter and tree sample points.*

the soil was similar but had not been disturbed by heavy machinery.

Undisturbed soil cores were collected on both occasion for determination of saturated hydraulic conductivity, soil moisture retention characteristics and bulk density (*cf.* Section 4.2) at 11 of the 25 selected grid points (see Appendix 25). Samples were collected at the surface (1–6 cm) before harvesting as well as after burning. Samples were also collected at a depth between 20 and 30 cm before harvesting, and near the bedrock (30–55 cm) after burning. When a road, track or landing been constructed on a sample point during harvesting, samples were collected at the sample point as well as from an adjacent undisturbed soil.

To obtain information on the impact of harvesting on the chemical composition of soil moisture and on variations in dry season soil moisture contents, a forested and a harvested plot (both 25*50 m) were established on the same slope near the catchment outlet at the beginning of October, 1990 (see Figure 15.3). Three pairs of vacuum tube lysimeters were installed along the slope in each plot to extract moisture from the topsoil (at -30 cm) and from the subsoil (at -60 cm). Sampling procedures were similar to those used in the forest plots as described in Section 13.2. Soil moisture extraction was possible until April, 1991, after which soil moisture levels prevented further extraction. One access tube for the capacitance soil moisture probe was installed at midslope position in each plot and the tubes were some 40 m apart. The access tube in the forested plot was installed on March 28, 1991, down to a depth of 110 cm, whereas that in the logged plot was installed on May 2, 1991, down to a depth of 54 cm. Profiles of θ were measured twice a week.

Changes in the mass and nutrient content of the litter layer following harvesting and burning were examined by comparison of samples collected before logging (December 13–17, 1990), shortly after completion of logging (August 2, 1991) and after burning of the slash (August 20, 1991) at 16 of the 25 sampling points of Figure 15.3. Sampling procedures were as in Section 11.2. Additional samples were collected on skidder tracks and landings close to several of the sample points. Stemwood and large branches could not be included in the sampling. On each occasion field and dry weights (70 °C) of the samples were determined. The samples collected at sample points 4,5,11,13; 27,34,36,42; 45,47,54,64 and 60,61,67,73 were bulked to obtain a set of four samples representing the whole catchment area. These were analysed at the Forest Research Institute in Rotorua, New Zealand, for macronutrients and micronutrients (with the exception of the first batch) as described previously.

Monitoring of streamflow amounts and composition (see also Sections 8.2 and 13.2) continued after the start of harvesting for the quantification of increased nutrient removal after the cyclone event, timber harvesting and burning of slash. The chemical composition of streamflow was studied from water samples collected during baseflow and stormflow events after harvesting started. Rising and falling stage collectors were installed in December 1990 (Schellekens, 1992) to facilitate the collection of such samples. The large sediment load of the streamflow during stormflow events prevented the filtering of water sampled for cation analysis. Hence no acidified samples could be collected in the field under these conditions, and instead samples were collected in 200 ml bottles and filtered and acidified in the laboratory at the FES-VUA before analysis. The effect of this procedure on the chemical composition of the sample was determined by comparing analysis of acidified and non-acidified samples collected simultaneously during periods with elevated sediment loads (but not such that samples could not be filtered in the field), which are shown in Table 15.1. No significant differences were observed between batches for Na, K, Mg, Ca and Mn. However, concentrations of PO_4, Si, Al, and Fe were significantly higher in the non-acidified samples, whereas NH_4

Table 15.1: *Comparison of means of samples filtered during sample collection, and samples filtered in the laboratory in the Netherlands. The comparison is based on 18 duplicate samples, concentrations are in mg* l^{-1}.

	Na	K	Mg	Ca	NH4	PO4	Si	Al	Fe	Mn
Filtered during collection (A)										
Average	8.79	1.91	2.64	1.40	0.14	0.03	8.1	0.34	0.23	0.01
SD	*1.44*	*0.66*	*0.73*	*0.65*	*0.05*	*0.06*	*2.7*	*0.62*	*0.17*	*0.05*
Filtered in the laboratory (B)										
Average	8.82	2.17	2.88	1.34	0.03	0.12	13.5	3.44	2.02	0.01
SD	*1.65*	*0.73*	*0.72*	*0.73*	*0.03*	*0.13*	*2.1*	*2.35*	*1.27*	*0.04*
A<>B	ns	ns	ns	ns	>***	<***	<***	<***	<***	ns

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance

was significantly lower in these samples, suggesting that sediment and organic matter present in the unfiltered sample absorbed NH_4, and released considerable amounts of the other ions. Several stormflow samples showing such unrealistic concentrations of NH_4, PO_4 and Si were discarded since the presence of sediment obviously influenced the analytical result.

15.2 Changes in the Vegetation – Litter Layer Complex

The impact of cyclone Sina, the removal of merchantable timber, and the burning of slash on the vegetation – litter layer complex will be discussed in this section, with the objective of quantifying the export of nutrients in timber from the catchment, as well as the changes in litter layer nutrient content after the various treatments.

15.2.1 Timber and Nutrient Exports

The biomass of merchantable timber (stemwood and bark) removed from the Oleolega catchment during harvesting between December 1990 and August 1991 was determined by TROPIK Wood Industries Ltd. The fresh weight of logs recovered from PU 10-3 (which includes both the Oleolega and Naruku catchments), amounted to 10411 tonnes and consisted for 20.5% of saw logs and 79.5% of pulp logs (pers. comm. Mr. J. Bale, Fiji Pine Ltd.). The dry weight was calculated using a conversion factor of 0.52 (Section 11.3.2). The amount of wood extracted from the Oleolega catchment could be calculated using the ratio of the forested area in Oleolega catchment (51.6 ha) to the total forested area in PU 10-3 (81.3 ha). Hence 3436 tonnes (dry weight) of wood were recovered from the catchment, or 54.6 t ha^{-1}. This included an estimated 6.6 t ha^{-1} of bark, which was used as fuel for power generation at the TROPIK Wood Industries Ltd. sawmill.

As the dimensions of the trees in the Oleolega catchment were not significantly different from those in Koromani forest ($\alpha = 0.01$) an estimate of the total pine biomass in the Oleolega catchment could be obtained by multiplying the pine biomass in

Table 15.2: *Average nutrient concentrations and standard deviations (SD) in harvestable timber sampled at various locations in the Oleolega catchment. The average dimensions of the sample trees are shown for comparison. Concentrations of macronutrients and micronutrients in % and in ppm, respectively, n represents the sample size.*

Site	N	P	K	Ca	Mg	Zn	Mn	B	n	Dbhob	h
Northern part (on dacite)											
Average	0.081	0.008	0.051	0.041	0.020	10	60	1.1	9	0.265	18.8
St. deviation	*0.011*	*0.002*	*0.011*	*0.012*	*0.003*	*4*	*30*	*0.2*		*0.029*	*1.0*
Southern part (on andesite/diabase)											
Average	0.084	0.013	0.056	0.046	0.021	13	47	1.4	5	0.276	19.4
St. deviation	*0.015*	*0.003*	*0.009*	*0.009*	*0.002*	*11*	*10*	*0.5*		*0.038*	*0.7*
Whole catchment											
Average	0.082	0.010	0.053	0.043	0.021	11	57	1.2	14	0.269	19.0
St. deviation	*0.012*	*0.004*	*0.010*	*0.011*	*0.002*	*7*	*27*	*0.3*		*0.033*	*0.9*

Koromani forest (Table 11.7) with the ratio of the stocking of Oleolega forest (459 trees ha^{-1}) to that of Koromani forest (621 trees ha^{-1}). This resulted in an estimate of 106 t ha^{-1} for the total pine biomass and of 86 t ha^{-1} for the stem biomass (including bark). The latter value is 1.6 times higher than that actually obtained earlier for harvested merchantable timber (54.6 t ha^{-1}), which may be explained by the fact that a large number of cyclone damaged trees with little or no economic value were left to rot in the field.

No data were obtained for undergrowth biomass, nor for biomass of the natural forest in the riparian zone. However, visual observation indicated that the density and composition of the undergrowth vegetation in the afforested areas of the Oleolega catchment were roughly comparable to those in the Koromani forest plot, and the undergrowth biomass was therefore assumed equal to 3300 kg ha^{-1}. However, this may well be an underestimate in view of the lower stocking of the forest at Oleolega.

Average nutrient concentrations in tree stems (wood and bark) sampled in the Oleolega catchment are given in Table 15.2. Averages for the northern part of the catchment, where soils were derived from dacitic rock (Chapter 4), were obtained from tree samples collected at locations B, C and D (Figure 15.3), whereas those for the southern part, where soils were derived from andesitic to diabase rock, were sampled at locations A and E. Phosphorus levels in tree stems growing in the southern part of the catchment were significantly higher ($\alpha = 0.01$) than in the northern part, possibly reflecting differences in soil or rock. Differences for the other nutrients were not significant.

Amounts of macro- and micronutrients exported from the catchment in merchantable timber between December 1990 and August 1991 are given in Table 15.3 together with estimates for the macronutrient export in bark only. The latter were obtained from the estimated total nutrient export using the average ratios of bark nutrient content to the total of stemwood and bark as observed in the Tulasewa, Korokula and Koromani forest plots (Table 11.17). The average ratios for Ca (0.18) and K (0.19) were lower than for N (0.25), P (0.25) and Mg (0.22). Differences between

Table 15.3: *Nutrient exports (kg ha^{-1}) from the Oleolega catchment in merchantable timber (stemwood & bark) and in bark only.*

Component	N	P	K	Ca	Mg	Zn	Mn	B
Stemwood & Bark	44.8	5.3	28.7	23.4	11.2	0.6	3.1	0.1
Bark	11.0	1.3	5.4	4.2	2.5			

the plots were small, with the exception of the ratio for P which ranged from 0.16 in Koromani forest to 0.40 in Korokula forest. No data were available in this respect for B, Mn and Zn.

Although the amounts of nutrients in timber exported from the catchment were small compared to the total nutrient content of the forest biomass (Section 11.6), they were much larger than the annual export of nutrients in streamflow from the catchment in the forested state (Table 13.14).

15.2.2 Litter Layer Mass and Nutrient Content

Cyclone Sina inflicted severe damage to the forest in the Oleolega catchment and the amount of litter on the forest floor at the end of November was therefore much higher than usual even before logging commenced in December 1990. Litter standing crop in December averaged 29,130 kg ha^{-1} (range 10,820–56,540 kg ha^{-1}, n= 16; Table 15.5) which was not significantly different (α= 0.05) from that measured in Koromani forest in January 1991 (22,688($\pm$4882) kg ha^{-1}, n= 12). As the damage afflicted to the Oleolega forest was comparable to that to Koromani forest (visual observation), the pre-cyclone litter layer mass observed in the latter (13,500 kg ha^{-1}; Table 12.7) may be used as an approximation for the pre-cyclone litter layer mass in the former.

The timber extraction procedure was such that the spatial heterogeneity of the litter layer was increased compared to the pre-logging heterogeneity. Several intensities of disturbance were distinguished which were associated with distinct phases in the timber extraction process. In the first extraction stage branches and foliage had not yet been stripped from the stem after logging by chainsaw, and the litter layer in an area several metres wide was pushed aside and accumulated in patches along the paths made by the trees when hauled (with a winch) to the skidder. This disturbance was considered to be of low intensity, and the mass of the litter layer sampled in these areas ranged from 2,960 kg ha^{-1} to 69,160 kg ha^{-1} (n= 16), with an average of 30,762($\pm$20137) kg ha^{-1}, which is somewhat larger than the post-cyclone range (10,820–56,540 kg ha^{-1}) and average. In the second stage trees (including the crown) were towed behind the skidder to a landing access road or landing. The disturbance of the litter layer on these skid tracks was more severe, especially after several passes had been made over the same track (*cf.* Kamaruzaman Jusoff, 1991). Litter under the tires of the skidder was pushed to the sides as well as into the soil, leaving the wheel tracks largely bare and causing an accumulation of litter along the edges of the track (*cf.* Gillman *et al.*, 1985). Where earth moving machinery had been used to construct access roads to the landings, a mixture of soil and litter accumulated along the roadside leaving the road surface free of litter. When litter samples collected in these areas were included, observed amounts of litter mass ranged from 1,380–153,380

Table 15.4: *Averages and standard deviations (SD) of nutrient concentrations (in % and ppm for macro- and micronutrients, respectively, n= 4) in the litter layer in the Oleolega catchment before harvesting, after harvesting, and after burning, as well as levels of significance for the differences between the means of the different treatments. Post-cyclone concentrations in the litter layers in Tulasewa, Korokula and Koromani forests are shown for comparison.*

	N	P	K	Ca	Mg	Zn	Mn	B
TULASEWA FOREST	0.725	0.049	0.138	0.558	0.189			
KOROKULA FOREST	0.608	0.029	0.084	0.501	0.221			
KOROMANI FOREST	0.685	0.040	0.091	0.559	0.181			
OLEOLEGA CATCHMENT								
Before logging (1)	0.745	0.038	0.246	0.379	0.142			
SD	*0.168*	*0.007*	*0.066*	*0.061*	*0.024*			
After logging (2)	0.779	0.054	0.240	0.344	0.166	30	654	9.3
SD	*0.109*	*0.014*	*0.069*	*0.062*	*0.025*	*2*	*171*	*0.9*
After burning (3)	0.747	0.175	0.283	0.497	0.364	44	821	11.9
SD	*0.136*	*0.023*	*0.102*	*0.116*	*0.128*	*8*	*401*	*2.5*
Difference in means of litter after treatments								
1 <> 2	ns	<*	ns	ns	ns			
2 <> 3	ns	<***	ns	<**	<**	<***	ns	<*

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

kg ha^{-1}, with an average of 37,185 kg ha^{-1} (Table 15.5), which is a factor 1.3 higher than the litter layer mass before harvesting started. However, as soil and litter were often well mixed, sampling of litter on the tracks was very difficult, and the actual range may have been much larger. The disturbance of the litter layer was considered to be of medium intensity on infrequently used skidder tracks (one or two passes), and of high intensity on frequently used tracks and access roads (more than two passes). In the third extraction stage trees were prepared for transport to the saw mill after arrival on the landings. This involved the stripping of the branches and foliage from the trees. To keep the landing area clear the slash was regularly pushed to the edges where it formed large piles consisting of a mixture of soil and slash. The spatial heterogeneity reached a maximum on these landings, and due to the size and composition of the piles no estimates could be obtained in these areas.

As a result of this increased spatial heterogeneity of the litter layer, it was difficult to determine whether the average value obtained from the limited number of sampling points was representative for the amount of litter present after the completion of harvesting. However, as the dimensions of the trees at Oleolega were similar to those in Koromani forest an independent estimate of the potential slash production could be obtained by using the pre-cyclone biomass data of Koromani forest (Table 11.7) corrected for differences in stocking. This resulted in a potential slash production of 22,600 kg ha^{-1} and with an estimated pre-cyclone litter layer mass of 13,500 kg ha^{-1}, the total mass of the litter layer after harvesting would be 36,100 kg ha^{-1}. This is close to the measured post-logging value, and the error in the areal estimate given earlier was therefore considered small.

The prescribed burn in August consumed the slash as well as the undergrowth

Table 15.5: *Averages and standard deviations (SD) for the litter layer mass and nutrient contents (kg ha^{-1}) in the Oleolega catchment before harvesting, after harvesting, and after burning, as well as levels of significance for the differences between the means of the different treatments.*

	Mass	N	P	K	Ca	Mg	Zn	Mn	B	n
Pre-cyclone+	13511	71.2	2.9	11.6	85.1	26.5	0.13	5.3	0.09	60
Before logging (1)	29130	206.9	10.8	71.7	108.2	40.7				16
SD	*12491*	*79.6*	*4.8*	*38.1*	*44.8*	*17.5*				
After logging (2)	37185	292.3	20.2	91.2	121.8	61.9	1.09	25.2	0.34	22
SD	*33632*	*278.4*	*20.3*	*92.6*	*100.0*	*56.8*	*0.96*	*26.6*	*0.30*	
After burning (3)	5787	46.7	9.7	18.9	27.1	25.4	0.28	6.1	0.07	19
SD	*7992*	*73.4*	*12.4*	*29.8*	*36.7*	*43.8*	*0.43*	*10.5*	*0.10*	
1 <> 2	ns	ns	<**	ns	ns	<*				
2 <> 3	>***	>***	>**	>***	>***	>**	>***	>***	>***	

+:Data from Koromani forest
ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

vegetation in the previously forested areas but did not have a large effect on the vegetation in the riparian zone. Post-burn measurements of the ash layer in the previously forested areas showed a significant decrease of the litter layer and undergrowth vegetation mass, from a pre-burn total of about 40,000 kg ha^{-1} to a post-burn total of 5,800 kg ha^{-1} (range 320–33,560 kg ha^{-1}, Table 15.5). As a result, after the burn the soil surface was exposed in most parts of the catchment.

The average nutrient concentrations in the litter layer on the three sampling occasions are shown in Table 15.4 together with the levels of significance for the differences between means (*Student's t* test). No significant differences were found for the concentrations of N, K, Ca and Mg in the litter layer before and after logging, but the concentration of P was significantly higher after logging. However, it must be remembered that the large input of fresh litter by cyclone Sina had already changed the concentrations of N, P, K, and Ca in the litter layer significantly as compared to the pre-cyclone composition (see Section 12.5.2). No data were available for the concentrations of Zn, Mn and B in the samples collected in December 1990. Burning of the litter layer had no significant effects on the concentrations of N, K and Mn but caused significant increases in the concentrations of P, Ca, Mg, Zn and B, suggesting that these elements were retained in the ash.

Litter layer nutrient contents for each treatment were calculated from litter layer mass and corresponding concentrations of nutrients. The results are presented in Table 15.5. The contents of all nutrients increased after harvesting, but the increases were only significant for P and Mg which increased by factors of 1.9 and 1.5, respectively. Again it must be stressed that cyclone Sina had increased the nutrient content of the litter layer considerably compared to the pre-cyclone situation (Table 12.7), and the effect of harvesting was therefore for a large part drowned by that of the cyclone. Litter nutrient content was reduced significantly by the burning, with post-burn amounts being 16% (N) to 48% (P) of the pre-burn contents. Therefore large amounts of nutrients were released from the slash during the fire, which greatly increased the

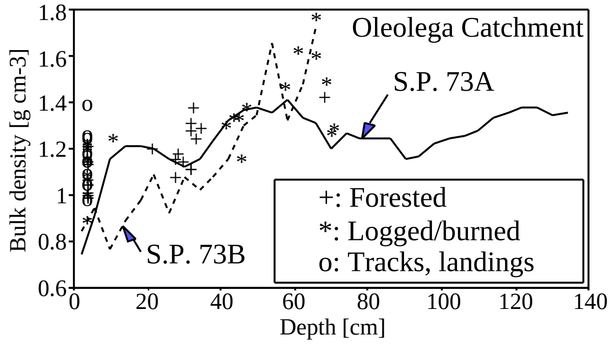


Figure 15.4: *Bulk density data for the soil at various locations in the Oleolega catchment.*

possibility of subsequent losses by leaching, or in overland flow during large storms (O'Loughlin *et al*, 1980; Hudson *et al.*, 1983b; Uhl and Jordan, 1984).

15.3 Impact of Harvesting on the Soil Physical Properties

Baseline data on soil physical properties have been provided in Chapter 4 and the effects of harvesting and burning on these properties are examined in this section.

15.3.1 Bulk Density

Figure 15.4 shows bulk density data for the Oleolega catchment collected before logging and after logging and burning of the slash. Two access tubes for the capacitance probe were installed close to sample point 73 (see Figure 15.3). Access tube S.P. 73A was installed in a small forest plot on relatively deep soil (rock at ±1.5 m) whereas access tube S.P. 73B was installed on the same slope at a distance of about 40 m from S.P. 73A in a shallow soil (rock at ± 70 cm) in a deforested area (see also Appendix 24). The two profiles compared well with bulk densities obtained from core samples (Appendix 25) collected at other sample points in the catchment (Figure 15.4).

To assess the impact of harvesting on soil bulk density, data collected for the upper 10 cm of soil in the forested state in December 1990 were compared with those collected in areas that had been logged and subsequently burned, but not disturbed otherwise, and with data collected on new roads, tracks and landings between August and October 1991. Due to the massive structure of the subsoil it was unlikely that harvesting and burning would have had a major effect below a depth of 30 cm (Van der Plas and Bruijnzeel, 1993) and the results obtained for the samples collected below this depth after logging and burning were therefore used to derive estimates for the bulk densities at intermediate depths for the pre-logging situation as well as for the soil under tracks, roads and landings. Estimates for depths up to 60 cm in the forested and in the logged and burned catchment are presented in Table 15.6, together with those for soils under roads, tracks and landings. Harvesting and burning greatly increased the spatial variation in bulk density as indicated by the increase in standard

Table 15.6: *Average bulk densities (g cm^{-3}), standard deviations, number of sample points and significance levels for the differences between means for soil samples collected in the Oleolega catchment in December 1990 (forested) and September 1991 (logged and burned; tracks & landings).*

Location	**Depth [cm]:**	0-10	10-20	20-30	30-55
Forested		1.07	0.535	1.21	1.41+
Standard deviation		*0.07*		*0.09*	
Number of samples		12		12	
Logged & burned		1.13	1.17	1.21+	1.41
Standard deviation		*0.11*			*0.17*
Number of samples		13			12
Tracks & landings		1.17	1.25	1.33	1.41+
Standard deviation		*0.11*			
Number of samples		10			
Differences in means between treatments					
Forested <> Logged & Burned		<*			
Forested <> Tracks & Landings		<**			
Logged & burned <> Tracks & landings		ns			

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.001; +: Assumed value; Underlined values have been obtained by linear interpolation

deviations. Although the sample sizes were small, the data suggested that the bulk density of the top 10 cm of soil increased significantly (α= 0.10) after harvesting and burning in the absence of further disturbance of the topsoil. This may have been due to degradation of soil aggregates (Lal, 1987). However, the increase was not large enough for the average value to fall outside the range observed for the soils in the forest plots (0.97–1.16 g cm^{-3}) and this increase should therefore not have a major impact on the productivity of a second rotation forest. Naturally, higher bulk densities were observed on tracks and landings where the topsoil had been disturbed severely and these were significantly different (α= 0.05) from those of the soil under forest but not from those of undisturbed soil after logging and burning. On the landings the growth of the newly planted second rotation forest may be poor due to the complete removal of the topsoil, which exposed the saprolite, or due to the severe compaction of soil and subsequent erosion (Assenberg, 1993). The high bulk densities observed in these areas may also impede root development (Van der Weert, 1974) which is likely to lead to lower productivity rates in the next rotation. It seems unlikely that the planting of pines on the roads and landings will improve the soil structure to a large extent.

15.3.2 Saturated Hydraulic Conductivities

Estimates of the hydraulic conductivity (K_{sat}) obtained from undisturbed core samples collected before and after logging and burning, as well as on roads, tracks and landings,

Table 15.7: *Averages, standard deviations (SD), medians, modes and ranges of K_{sat} for top- and subsoils before and after harvesting and burning in the Oleolega catchment and for the top 10 cm after construction of tracks and landings.*

Treatment	Depth [cm]	Average [m day-1]	SD	Median [m day-1]	Mode [m day-1]	Minimum [m day-1]	Maximum [m day-1]	n
Forested	1-6	73	73	52	27	0.1	225	12
Logged & burned	1-6	15	41	1.5	1.06	0.01	153	14
Tracks & landings	1-6	0.17	0.23	0.049	0.043	0.0001	0.69	11
Forested	25-35	3.1	5.3	1.22	0.58	0.06	19	12
Logged & burned	40-70	0.05	0.08	0.0088	0.0082	0.0004	0.24	13

are shown in Table 15.7. Data for the individual samples are given in Appendix 25. Although the sample sizes were small significant differences were observed between the various intensities of disturbance. The K_{sat} of the topsoil decreased significantly (α= 0.01) as a result of the forest clearance and subsequent burning of the slash, possibly due to a collapse of the soil structure as a result of raindrop impact and exposure to solar radiation (Lal, 1987).

The K_{sat} of compacted topsoil of tracks, roads and landings was significantly lower (α= 0.01) than measured in adjacent relatively undisturbed soils. Widespread overland flow and erosion was indeed observed on these compacted surfaces during larger storms but not in the adjacent less disturbed areas (Assenberg, 1993). The impact of these changes on the streamflow hydrograph and water quality will be discussed in Section 15.6.

15.3.3 Porosity and Moisture Retention

The modelled (Van Genuchten, 1980; see Appendix 25) average pre-harvesting porosity of core samples collected in the top 6 cm of soil (60±6%; Table 25.10) at nine points in the catchment on which roads, tracks or landings were later constructed during harvesting was not significantly different from that derived after the burn on these tracks, roads and landings (57±4%, n= 9; Table 25.14), nor from that derived for the adjacent relatively undisturbed locations (62±5%, n= 9; Table 25.12).

However, the porosity of the soil of tracks and landings (Table 25.14) was significantly lower (α= 0.05) than of the soil in adjacent areas subjected to logging and burning but without disturbance by heavy equipment (Table 25.12). This was supported by the fact that macropores, which were abundant in the undisturbed soils, were not observed in the compacted soils on roads and landings (*cf.* Jetten, 1994). However, as the difference was rather small the decrease in pore size may in some way have been balanced by an increase in the number of smaller-sized pores. Since soil moisture retention characteristics are likely to change as a result of changes in pore size (increasingly higher suctions are needed to remove moisture from pores of decreasing size), a study of the corresponding moisture retention characteristics should indicate whether such a change occurred. Figure 15.5 shows the average moisture retention curves for the pre- and post-harvesting/burning periods as well as for soils on tracks, roads and landings. Moisture retention data for individual core samples are given in

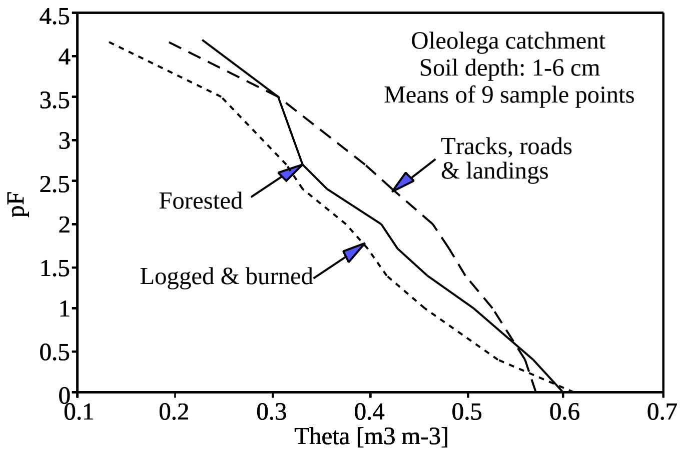


Figure 15.5: *Average moisture retention curves for the topsoil in Oleolega catchment before and after logging and burning and on tracks, roads and landings.*

Appendix 25. Although the average post-harvesting/burning porosity of topsoil in areas not disturbed by heavy machinery was higher than that of topsoil on adjacent roads, tracks and landings, the average below field capacity (pF= 2) moisture content was significantly lower (α= 0.05 for 0.4<pF<1.4 and 0.10 for pF= 1.7–2.0). This indicated that a reduction in (macro)pore size had indeed occurred as higher suctions were now needed to remove water from topsoil on roads, tracks and landings. Differences between the moisture retention of soil under forest and on tracks, roads and landings were not significant below a pF of 1.0 but above this value significantly higher moisture contents (α= 0.10 for pF= 1.4 and 0.05 for pF>1.4) were again observed for the latter (Figure 15.5). The moisture content above pF= 2.0 of the samples collected under forest was modelled (Van Genuchten, 1980) due to lack of laboratory facilities in Fiji, whereas those for the samples collected after logging and burning were actually measured. Therefore, it was not possible to determine if the observed changes in the soil moisture retention characteristics affected soil water holding capacity. However, the present data do not suggest any major change in the water holding capacity. However, as the removal of soil (*e.g.* on roads and landings) reduced the soil depth (already low on the ridges), the amount of water available for plants will have been reduced accordingly. Hence second rotation forest planted on landings and roads may experience periodic water stress during the dry season and this, in combination with the poor structure of the compact soil will almost certainly lead to lower productivity. Due to the small textural differences between topsoil and subsoil the impact of logging and burning on soil texture could safely be neglected and therefore no granulometric analyses were done on samples collected after logging and burning.

The observed changes in porosity and moisture retention were similar to those observed by Kamaruzaman Jusoff (1991), who studied changes in porosity and available water holding capacity after up to 50 passes were made with a crawler tractor and a rubber tyred loader on undisturbed clay loam soil during wet and dry months in Central Pahang, Malaysia. Kamaruzaman Jusoff (1991) observed that the porosity decreased from 46–47% to 37–41%. Shifts in the soil moisture retention curves were also observed and this resulted in a decrease of the available water holding capacity from 100–110 mm m^{-1} to 83–94 mm m^{-1} after 50 passes. The largest changes were observed during the first 2–4 passes of the vehicles and changes caused by the rubber tyred loader were larger than those by the crawler tractor which was attributed to differences in contact pressure. Dias and Northcliff (1985a,b) also observed decreases in the number of macropores (from 20% in undisturbed topsoil to about 7% after several tractor passes) and the topsoil water holding capacity of a clayey Oxisol after clearing of rainforest in Amazonia, with the largest changes after mechanical clearing by bulldozers.

15.4 Impact of Harvesting Soil Chemical Properties

The effect of logging and subsequent burning of the slash on soil chemical characteristics in the Oleolega catchment was studied by comparing samples collected before logging started with those collected after the burn. The samples representing the forested situation, were collected in December 1990, shortly after cyclone Sina had deposited salts (sea spray, Table 13.4) and large amounts of fresh litter (Table 12.7) on the soil surface. However, the amounts of nutrients deposited as sea spray were small compared to the corresponding nutrient reserves in the soil (Table 4.10) and because rainfall in the period between the passage of the cyclone and the collection of samples had been low (17 mm) the transfer of nutrients from the freshly deposited litter to the soil by leaching (*e.g.* K) was neglected. As such the influence of the cyclone on the soil chemistry at the time of sampling was considered small.

The post-burn samples were collected between 5 September and 1 October 1991. On the other hand, some 66 mm (September 5) to 224 mm (October 1) of rainfall was recorded after the burn, which was considered sufficient to transfer readily soluble nutrients present in the ash to the soil. The loss of nutrients from the litter layer and slash following the burn was discussed in Section 15.2.2 (Table 15.5). Average values for various chemical properties of the soil before and after logging and burning are presented in Table 15.8, whereas the raw data are listed in Appendix 26. The effects of logging and burning were most evident in topsoil and the largest differences were observed between soil under forest and that of tracks and landings. Exchangeable NH_4 decreased significantly whereas the pH_{H2O} and the pH_{KCl} showed significant increases throughout the soil profile after logging and burning. The increase in pH_{H2O} was sufficient to bring the soil from the cation exchange buffer range to the silicate buffer range (Ulrich and Khanna, 1984). Ca-lactate extractable PO_4 did not show significant changes in topsoil after burning but increased in subsoil. No significant changes for other soil chemical characteristics were observed in the subsoil. Exchangeable K increased whereas exchangeable NO_3 decreased in the topsoils of relatively undisturbed areas and tracks and landings after logging and burning. Exchangeable Na showed a significant decrease and exchangeable Ca a significant increase in the 0–10 cm layer of the soil in relatively undisturbed areas but neither was the case for the soils of tracks and landings.

The N content did not change significantly after harvesting and burning in areas where the topsoil was not disturbed by heavy equipment, but it was significantly lower in the surface layer on tracks and landings due to the removal of N-rich topsoil. However, no significant changes were observed in for the carbon content. As a result,

Table 15.8: *Chemical properties of the soil at several depths before logging started in the Oleolega catchment, and after harvesting had been completed and the slash had been burned. The sample size is represented by n, the depth is in cm, the LOI is in % whereas exchangeable cations, available PO_4 and soluble NO_3 are in meq 100 g^{-1} soil.*

Location	Depth	n	pH	pH*	%N	%C	C/N	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
Oleolega	0-10	25	4.60	3.97	0.136	2.22	18.0	8.3	0.170	0.114	1.28	1.93	0.170	0.129	0.013
Forested	10-20	25	4.56	3.87	0.084	1.25	15.7	7.1	0.118	0.081	0.75	1.67	0.133	0.068	0.004
	30-60	25	4.72	3.83	0.033	0.37	11.4	6.2	0.127	0.062	0.29	2.06	0.070	0.025	0.001
Oleolega	0-10	25	5.25	4.26	0.130	2.17	20.9	8.7	0.111	0.179	1.73	2.43	0.103	0.042	0.012
Logged &	10-20	25	5.16	4.12	0.077	1.25	21.9	7.6	0.101	0.120	1.16	2.20	0.065	0.025	0.003
Burned	30-60	25	5.01	4.01	0.034	0.43	15.0	6.5	0.105	0.052	0.32	2.46	0.011	0.024	0.002
Oleolega	0-10	14	5.14	4.19	0.079	2.16	27.8	9.6	0.147	0.158	1.32	2.65	0.097	0.039	0.008
Tracks &	10-20	14	5.17	4.10	0.065	1.57	25.3	9.1	0.111	0.119	0.86	1.99	0.067	0.030	0.007
Landings	30-60	14	5.36	4.03	0.023	0.29	13.2	7.3							
Significance levels of differences between means by Student's t-test															
Depth interval 0-10 cm															
Forested <> Logged			<***	<***	ns	ns	ns	ns	>***	<***	<*	ns	>***	>**	ns
Forested <> Tracks			<***	<**	>**	ns	<***	<*	ns	<***	ns	ns	>**	>**	ns
Logged <> Tracks			>*	ns	>**	ns	ns	ns	<**	ns	ns	ns	ns	ns	ns
Depth interval 10-20 cm															
Forested <> Logged			<***	<***	ns	ns	ns	ns	ns	<***	<**	ns	>***	>***	ns
Forested <> Tracks			<***	<**	ns	ns	<***	<**	ns	<*	ns	ns	>***	ns	ns
Logged <> Tracks			ns	ns	ns	ns	ns	<**	ns	ns	>*	ns	ns	<*	<*
Depth interval 30-60 cm															
Forested <> Logged			<***	<***	ns	ns	ns	ns	ns	ns	ns	ns	>***	ns	<*
Forested <> Tracks			<***	<*	ns	ns	ns	ns							
Logged <> Tracks			<***	<*	>*	>*	ns	ns							

pH*: pH of soil in KCl solution
ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01

the C/N ratio of the topsoil on tracks and landings increased significantly after logging and burning but the observed increase in relatively undisturbed areas was not significant due to the large standard deviation calculated for the post-logging samples (16.9–21.7). The standard deviation of the C/N ratio in the soil before logging ranged from 4.0 in the topsoil to 5.5 in the subsoil and the increase observed after logging and burning suggested a much higher spatial variation throughout the soil profile. The standard deviation on tracks and landings ranged from 5.8 to 6.6 and was therefore comparable to that of the subsoil before logging. Surprisingly, the %LOI of the topsoil on tracks and landings was significantly higher than that of the soil under forest.

Total amounts of available nutrients in the soil before and after logging and burning are given in Table 15.9 together with the estimated enrichment of the soil. The overall totals for the post-logging and burning period were calculated from the respective values observed for relatively undisturbed soils and soils on tracks and landings weighted by the area covered by each soil type.

Total amounts of available K, Ca, Mg and total C increased as a result of harvesting

Table 15.9: *Total amounts of available nutrients, N and C (kg ha^{-1}) in the 0–60 cm soil layer of the Oleolega catchment before and after harvesting and burning and the enrichment due to logging and burning.*

	Na	K	Ca	Mg	P+	P*	NH4-N	NO3-N	N-Tot	C-Tot
Oleolega Forest	230	220	816	1837	2.7		105	53	4513	63563
Logged & burned areas	211	280	1084	2006	2.4		80	30	4798	73090
Tracks & landings	231	280	923	2063	2.9		82	32	3313	69183
Oleolega Logged & Burned	213	280	1069	2011	2.4		80	30	4654	72711
Nutrient enrichment	*-17*	*59*	*252*	*174*	*-0.3*		*-25*	*-23*	*141*	*9148*

P+: Ca-Lactate extraction method; P*: Bray II extraction method, estimates for soil pits

and burning, partly because of increases in the concentrations (K, Ca) and partly because of increases in bulk density (Mg, C). The total Ca-Lactate extractable P content did not change. No data was available for amounts of 'available' P according to the P-Bray II method. The total N content increased but corresponding available totals of NH_4–N and NO_3–N decreased suggesting that the increase of N was mainly in the form of organic compounds or ash. Non-decomposed ash particles were indeed observed in the topsoil samples collected after logging and burning. The errors in the given totals may be considerable due to the limited number of samples used in the calculations but the values seem realistic in view of the totals released from the litter layer after the burn as given in Table 15.5.

No information was available on the effects of harvesting and subsequent burning of slash of pine plantations growing on former grassland soils in the tropics. Russell (1983) observed an increase in soil pH (from 3.9 to 4.8 in the top 5 cm) and available P, K, Ca and Mg, but not in total N, in a sandy Ultisol after clearing of rainforest and burning of slash. Soil nutrient contents declined below those observed under adjacent rainforest during the growth of *Pinus caribaea* and *Gmelina arborea* (except total N and Ca) forests planted on these soils. Available K, Mg and total N increased again after harvesting of an 8.5-year-old *Gmelina arborea* plantation, whereas available P and Ca decreased.

Uhl and Jordan (1984) observed increases in pH (from 3.2 to 3.5) and exchangeable Ca, Mg and K, but not in total P and total N, in topsoil (0–10 cm) five years after cutting and burning of rainforest on a sandy Oxisol.

In a prescribed burning experiment (low intensity burn) of *Pinus oocarpa* planted on sandy soils in Honduras, Hudson *et al.* (1983b) observed increases in available K and Na, but not in available Mg and P, whereas a decrease in available Ca was observed.

In the coastal lowlands of Florida, Fisher (1981) observed a decrease in total N in the upper 25 cm of a wet sandy Ultisol one year after harvesting of *Pinus elliottii* forest, site preparation (chopping and bedding, no burn) and replanting, although fertilizer (N and P) was applied during planting. In contrast to total N, extractable P and Ca were higher one year after the treatment. Relatively small changes were observed for K and Mg.

Stromgaard (1984) observed changes in the soil stores of N, P, K, Ca, Mg and Na in a *chitimene* shifting cultivation experiment on a sandy soil (pH$\approx$ 4.7) in NE Zambia, where biomass of surrounding areas was collected in piles and burned to improve soil fertility. Increases in available K, and to a much lesser extent in N and P stores, were observed within 24 hours after the burn. The increase of P was delayed and a major increase in the store of this element was only observed 40 days after the burn. A decrease in available Ca was observed immediately after the burn but higher levels were observed after 40 days. Available Mg and Na decreased after the burn.

In Malaysia, Ghulam and Norhayati (1989) observed relatively small changes in soil chemical properties six months after felling of rainforest on a sandy clay loam to clay loam soil. Much larger changes were observed in the soil nine months after the site was prepared (slash burned) for rubber cultivation. Burning resulted in a 25% decrease in the organic carbon content and a slight decrease in total N, whereas exchangeable K, Ca and Mg and available P increased by 88%, 219%, 68% and 83%, respectively, of their values under forest. Fifty months after the planting of rubber trees and cover crops, exchangeable K and Mg were down to their levels measured under rainforest, whereas exchangeable Ca had declined as well but was still 71% higher than its level under rainforest. Soil pH increased from 4.1 under rainforest to 4.5 after burning and decreased again to 3.9 50 months after planting of rubber trees and crops. In contrast, Amir (1989) observed a significant decline in soil pH and contents of N, P, C, Mg and Na and CEC after logging of rain forest on sandy clay to clay loam soils in Malaysia. The content of K, however, increased immediately after logging, but returned to its initial value one year after logging.

All these experiments were on acid, nutrient-poor, mostly sandy soils with much lower CEC values than those observed for the present study sites. As such the capacity of these soils to retain nutrients released after the conversion must be considered low and this resulted in enhanced leaching of soil nutrients in runoff following the conversion (Fisher, 1981; Hudson *et al*, 1983b; Stromgaard, 1984), especially in areas with high rainfall (Russell, 1983; Uhl and Jordan, 1984). Furthermore, the amounts of nutrients released during the burn in these studies were higher than those released by the burn in the Oleolega catchment. As such the soils in the Oleolega catchment are more likely to retain these nutrients, thereby limiting leaching losses after the burn (*cf.* Section 15.6.3).

15.5 Effect of Harvesting on Soil Moisture

15.5.1 Soil Moisture Content

The effect of harvesting on soil moisture profiles with depth was evaluated by comparing the dry season variation of soil moisture in a forested plot (plot A) with that in an adjacent area that had been logged (plot B) in December 1990 (Figure 15.3). The measured dry season variations at various depths at the two locations are shown in Figure 15.6. The reduction in moisture extraction for transpiration at the deforested site resulted in a much slower decrease of θ compared to that observed under forest. As there was little vegetation left around the access tube in the deforested area, the decreased variation in topsoil θ may be attributed largely to evaporation from the soil.

A gradual decrease in θ was observed in the subsoil under forest during the dry season until mid September when the soil moisture was replenished by large storms. Drainage to groundwater from the root zone during this period could be neglected. In contrast, the subsoil in the harvested area did not show any signs of soil moisture depletion and remained moist throughout the dry season (Figure 15.6). These trends

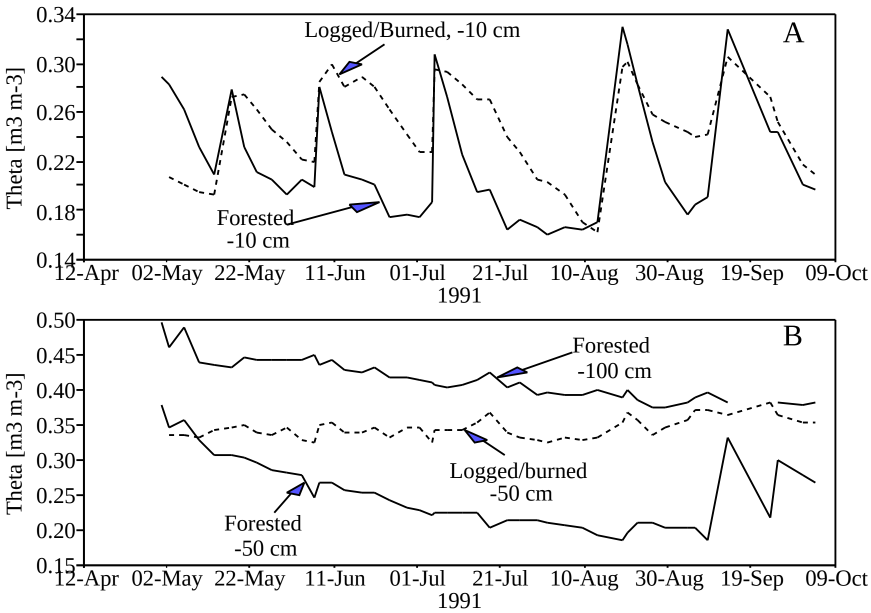


Figure 15.6: *Dry season variations of θ in topsoil (A) and subsoil (B) before and after deforestation.*

are in agreement with the results obtained for the respective forest plots (Section 6.5) and the Nabou grassland (Section 5.3).

15.5.2 Soil Moisture Chemistry

An attempt was made to determine the impact of harvesting on the chemical composition of soil moisture by comparing samples collected in the forested and harvested plots at Oleolega, referred to in the previous section. Collection of soil moisture started in October, 1990, when both plots were under forest and the period served as a calibration period until the occurrence of cyclone Sina on 27–28 November (*cf.* Hewlett and Fortson, 1983). The cyclone severely defoliated the forest and also deposited sea spray on the ecosystem. One of the plots (Plot B) was subsequently logged on January 17, 1991. No soil moisture could be extracted anymore by the end of April, 1991, due to drying out of the soils. As such the data pertains to the wet season of 1990–1991. Weighted averages of the ion concentrations in soil moisture for the pre-cyclone, post-cyclone and post-harvesting periods are shown in Table 15.10. The spatial variation in pre-cyclone chemical composition of soil moisture was high, as indicated by the differences between sites. A high NO_3 concentration was measured by the lysimeter pair in the mid slope position in the forested plot (plot A), but not by the other pairs in the same plot. The deposition of sea spray, and large amounts of fresh litter on the forest floor by the cyclone caused large changes in soil moisture chemical composition, similar to the ones discussed for the other sites in Section 13.6. The highest concentrations were observed shortly after the cyclone passed, whereas concentrations had decreased somewhat before one of the plots was logged, *i.e.* six weeks after the event.

Table 15.10: *Mean weighted concentrations (mg l^{-1}) of top- and subsoil moisture of two forested plots (A and B) before and after cyclone damage (November 28, 1990) and clearfelling (Plot B only on January 17, 1991, not burned) for the period October, 1990 – April, 1991*

Location	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
								TOPSOIL (-30 cm)										
Pre-cyclone																		
Forested A	105	6.21	6.4	1.56	6.9	1.73	0.30	13.2	8.5	2.9	24.8	0.06	6.3	0.02	0.02	0.03	0.53	0.02
Forested B	86	6.27	7.2	0.52	5.3	0.91	0.24	13.9	15.7	4.2	5.5	0.01	5.6	0.02	0.02	0.02	0.76	0.02
Post-cyclone																		
Forested A	162	6.40	13.3	2.13	8.5	2.40	0.18	41.6	6.1	5.6	18.8	0.01	6.0	0.10	0.02	0.06	0.49	0.02
Forested B	138	6.58	10.1	0.72	9.7	0.99	0.23	33.6	10.2	3.3	6.0	0.02	5.3	0.08	0.02	0.02	0.41	0.02
Post-harvesting																		
Forested A	155	6.06	12.0	1.67	9.1	1.79	0.17	30.6	6.7	4.3	19.9	0.03	6.1	0.05	0.02	0.02	0.56	0.03
Logged B	110	6.47	8.5	0.48	7.4	0.74	0.16	23.2	11.7	3.7	1.2	0.02	5.1	0.05	0.02	0.02	0.42	0.03
								SUBSOIL (-60 cm)										
Pre-cyclone																		
Forested A	89	6.34	9.6	0.84	5.3	0.52	0.21	9.1	22.5	4.6	8.4	0.01	7.8	0.02	0.02	0.02	0.29	0.02
Forested B	120	6.70	9.5	0.23	10.4	0.78	0.06	14.7	44.5	4.8	2.3	0.01	7.7	0.03	0.02	0.02	0.31	0.02
Post-cyclone																		
Forested A	119	6.39	11.9	0.31	8.5	0.56	0.20	19.5	16.5	4.8	10.4	0.02	7.7	0.08	0.06	0.02	0.35	0.02
Forested B	155	7.02	11.0	0.22	12.4	0.61	0.28	26.5	38.0	4.3	5.8	0.02	7.7	0.10	0.02	0.02	0.34	0.02
Post-harvesting																		
Forested A	112	6.40	11.6	0.48	6.6	0.29	0.22	19.5	12.3	2.8	11.4	0.02	6.6	0.05	0.02	0.02	0.43	0.03
Logged B	145	6.75	10.2	0.24	13.0	0.53	0.25	21.9	37.6	3.5	3.3	0.02	7.4	0.05	0.02	0.02	0.32	0.03

The impact of the cyclone was such that any changes in the soil moisture chemistry as a result of logging were drowned in the changes already caused by the cyclone. It proved impossible, therefore, to evaluate the impact of harvesting separately. No samples could be collected after the burn in August, 1991, because soil moisture levels remained low due to lack of rainfall in the post-burn period.

15.6 Impact of Harvesting and Burning on Water Use and Quality

15.6.1 Water Use

Water yield from the Oleolega catchment was expected to rise following harvesting due to the associated decrease in evapotranspiration, as has been observed after clearing catchments planted to pines in the warm temperate zone (Douglas and Swank, 1975; Pearce and Griffiths, 1980; Swindel *et al.*, 1983a,b,c; Hewlett *et al.*, 1984; Hsia, 1987; Rijsdijk and Bruijnzeel, 1991; Smith and Scott, 1992). Furthermore, the increase in area with a compacted surface (*e.g.* landings, roads) from 2.4 to 6 ha, in combination with the higher soil moisture levels after harvesting, might affect the rainfall–runoff response of the catchment as well. This section discusses the results.

Independent ET rates were determined from soil moisture depletion data collected in the forested and clearfelled plots within the catchment already referred to earlier (Figure 15.3) using the method described in Section 6.5. Only a single access tubes had been installed in each plot and spatial variations in ET_{sm} could therefore not be evaluated. Spatial variation was presumably high, with large differences between the soil moisture status and thus ET in the riparian zone and on the ridges. Hence the values presented here serve only to illustrate the difference in ET_{sm} between the two plots, rather than providing accurate estimates for the whole catchment. The average daily ET_{sm} calculated for the forested plot during the period May 20 until October 4, 1991, averaged 2.11(±1.17) mm day^{-1} (n= 94), whereas that of the deforested area was 28% lower at 1.52(±0.79) mm day^{-1} (n= 94). The forest was capable of extracting moisture from depths below that of the access tube and the ET_{sm} will therefore have been underestimated (*cf.* Section 6.5). Because ET_{sm} for the deforested area may be considered accurate, the actual reduction after clearance could be somewhat higher than 28%.

The simplest method to determine the impact of timber harvesting and subsequent burning on the catchment water use would be a direct comparison of pre- and post-logging ET values obtained from water balance calculations over the respective periods. However, the results of this approach would only be reliable if the amounts and distribution of rainfall in the two periods would be comparable and when changes in soil moisture and groundwater storages can be evaluated properly. Whilst it is recognized that a paired catchment study might yield more reliable results (Bosch and Hewlett, 1982; Hewlett and Fortson, 1983), such an approach was not possible in the present context. Therefore in the following a judicious comparison of water balances for the respective periods is offered. This will be followed by an application of the single-catchment approach of Ibrahim and Chang (1989). The effect of cyclone Sina and partial logging of the catchment (up to 50% clearfelled until May, 1991) on basin water use was studied by Assenberg (1993). However, because he used a preliminary stage – discharge relation which overestimated peak flows (*cf.* Section 8.2), his estimate of 3.5 mm day^{-1} for the initial post-logging period December 1990 – May 1991

Table 15.11: *Regression constants and coefficients of determination (CD) for the best fits of wet and dry season master recession curves for the Oleolega catchment after harvesting and burning.*

Recession Curve	Q1	Q2	K1	K2	CD
Wet Season 1992	0.044	0.124	0.958	0.420	0.99
Dry Season 1991	0.030	0.130	0.970	0.180	0.96

will have been too low. A new estimate was calculated with the water balance method for the 151 days period between January 1 and May 31, 1991. To determine ΔG, a new master baseflow recession curve was constructed graphically, and non-linear regression analysis (Marquardt, 1963) yielded values for Q_1 (0.027 mm h^{-1}), Q_2 (0.172 mm h^{-1}), K_1 (0.920) and K$_2$ (0.480) in Equation 8.4. Applying the latter coefficients to the period under consideration resulted in a ΔG of less than 0.1 mm, which could be neglected safely. Rainfall totals in the months prior to the start (P= 84 mm) and end of the period (P= 35 mm) differed by 49 mm, and ΔS could therefore not be neglected and was, somewhat arbitrarily, set at -34 mm (0.7$\cdot\Delta$P).

Total rainfall between January 1 and May 31, 1991, amounted to 855 mm, whereas the corresponding streamflow output amounted to 200 mm, resulting in an ET of 689 mm, or 4.6 mm day^{-1}. The corresponding E$_0$ amounted to 5.2($\pm$1.4) mm day^{-1}, implying an ET/E$_0$ ratio of 0.88 which is considerably lower than that obtained for the wet season a year earlier (1.06, Section 8.3). Because the amounts of rainfall during both periods were comparable and evapotranspiration could be at its potential rate as soil moisture was not limiting, the lower ET/E$_0$ ratio for 1991 would suggest that water use had indeed decreased after harvesting commenced, although some of the effect must undoubtedly be attributed to a decrease in the evaporative surface (LAI) following cyclone Sina (*cf.* Section 11.3.6).

The difference in water use was likely to increase with the size of the area cleared from pines (Bosch and Hewlett, 1982; Bruijnzeel, 1990). Therefore catchment water use was also determined for the 284-day period between June 24, 1991 (86% logged) and April 2, 1992 (undergrowth regeneration following logging and burning). Master depletion curves for the dry and wet season during this period were constructed by Van Well (1993b) using non-linear regression analysis (Marquardt, 1963; *cf.* Equation 8.4). The resulting regression constants are given in Table 15.11.

The period was chosen in such a way that the discharge at the beginning of the period (0.54 mm day^{-1}) was similar to that at the end (0.51 mm day^{-1}) so that changes in groundwater storage could again be neglected. Rainfall totals for the months preceding the beginning and end of the period were 36 and 5 mm, respectively, and ΔS was therefore neglected as well. A rainfall total of 887 mm was recorded whereas a total of 181 mm was discharged during the post-harvesting period. The water balance approach thus yielded an estimated ET of 706 mm, or 2.5 mm day^{-1}, suggesting a reduction in water use of 39% as a result of harvesting and burning (pre-harvesting ET was 4.1 mm day^{-1}; *cf.* Section 8.3). Because the above-ground dead and live biomass was low for most of the post-harvesting period, rainfall interception by the vegetation – litter layer complex during this time was assumed to be less than 5% of total rainfall (*cf.* Section 5.5). Therefore the amount of water reaching the soil was in the range of 840–890 mm, or 3.0–3.1 mm day^{-1}. This was 14–17% less than the average daily amount of water reaching the soil in the period for which the water use of the forested catchment was determined ($\bar{P}$= 3.6 mm day^{-1}, Section 8.3). Despite the lower rainfall inputs as compared to those in the the pre-harvesting period, the runoff coefficient increased from 0.16 to 0.21. However, the influence of the difference in rainfall amounts between the periods on the magnitude of ET may perhaps not be neglected entirely, and a simple runoff simulation model developed for the forested catchment (Schellekens, 1992) was used to explore this further.

The model used a shape parameter derived from a master unit hydrograph (Nash, 1957, 1959), and a set of regression equations to compute stormflow volume (SV) and duration from the hourly mean areal precipitation (P) and a 7-day antecedent precipitation index (API_7). The API was calculated from the following formula (Viessman *et al.*, 1977):

$$API_7 = \sum_{t=1}^{t=7} P_t K^t \tag{15.1}$$

where t is the number of days before the day for which the API is calculated, P_t the rainfall total on day t, and K a constant taken as 0.82 (Schellekens, 1992, following Ward and Robinson, 1990). The equation for the prediction of the stormflow volume was of the form:

$$SV = \exp^{(a \ln P + b \ln(API_7+1)+c)} \tag{15.2}$$

where a, b and c are regression coefficients. Their values were obtained using regression analysis on a pre-harvesting dataset containing 40 storms, and amounted to 1.814(±0.149), 0.457(±0.108) and −8.213(±0.560), respectively, with a coefficient of determination of 0.81 (Van Well, 1993b). To account for variations in baseflow rise due to precipitation, a treshold value of 10 mm was introduced. No baseflow rise was assumed to occur during storms below this value (Schellekens, 1992).

During periods of baseflow recession the master depletion curves obtained for the forested catchment in Section 8.3 were used to simulate streamflow. Total flow was determined by adding stormflow volumes to the baseflow volumes. More details on the model are provided in Schellekens (1992).

To test the predictive capacity, it was run for the rainfall data collected during the pre-harvesting calibration period. Model prediction for the period January 4 – November 13, 1990 (192 mm) was poor, being some 22% lower than the measured streamflow total (247 mm). However, if the extreme rainfall associated with cyclone Rae in March 1990 was excluded, model prediction improved to a 6% underestimation of the measured streamflow total, which is within the combined measurement errors of rainfall and streamflow. As such the model seemed to perform well under normal rainfall conditions, but not during extreme rainfall events when quickflow is seriously underestimated by the model. Because such extreme rainfall events were not encountered during the post-harvesting period, a comparison of the streamflow predicted for the forested catchment with measured streamflow after harvesting may provide a good indication of changes in water use and yield following harvesting.

Van Well (1993b) compared the observed streamflow total from the logged and burned catchment (163 mm), measured in the period between August 1, 1991, and March, 31, 1992 (243 days) with the predicted total for the catchment in the forested state (115 mm) using the corresponding rainfall data (822 mm), and obtained an ET of 2.7 mm day^{-1} as opposed to a modelled ET of 2.9 mm day^{-1}. However, the period was not chosen in such a way as to minimize errors in ΔS and ΔQ, and the calculated

ET may therefore not be accurate. To minimize these errors, the model was rerun for the period June 24, 1991 – April 2, 1992 (283 days). Changes in groundwater storage during this period could be neglected since discharges at the beginning and end of the period were equal. As rainfall totals for the months preceding the beginning and end of the period differed little (36 *versus* 25 mm) ΔS could be neglected as well. Total rainfall during this period amounted to 886 mm, whereas the observed streamflow output amounted to 181 mm, implying an ET of 705 mm, or 2.5 mm day^{-1}. The model predicted a streamflow output of 120 mm, corresponding with an ET of 766 mm, or 2.7 mm day^{-1}, which was only 10% lower than the value obtained for the similarly aged Koromani forest during the dry season of 1991 (2.96 mm day^{-1}; Section 7.7).

Due to the rather low rainfall input during the post-burn period, modelled interception losses from the forest canopy (Gash, 1979) and litter layer (this study) were relatively low at 170 mm and 90 mm, as compared to those modelled for the same period a year earlier (294 and 138 mm, respectively) when rainfall (1536 mm) was closer to the long-term average (Section 6.3).

In this dry year, harvesting of the forest reduced catchment ET by some 0.2–0.4 mm day^{-1}, or 7–14%. Although the difference in water use seemed small, the gain in water yield was considerable, with the observed streamflow being 51% higher than that predicted for the forested catchment. In years with rainfall being closer to the long-term average, the difference between the forested and cleared situation can be expected to be even larger due to higher evapotranspiration losses from the forested catchment (see Table 9.2), as well as higher stormflow amounts from the cleared catchment (*cf.* Malmer, 1993).

15.6.2 Effect of Harvesting on Minimum and Peak Flows

Changes in minimum and peak flows are of particular interest, since it is under these conditions that changes in the hydrologic regime have the greatest economic implications, either through water shortages, or through damage to infrastructural works, property and crops by flooding and sedimentation.

If minimum flows at Oleolega would not be influenced by the change in forest cover, the below average rainfall in the post-harvesting period would have reduced the minimum flows from the catchment compared to those observed in the pre-harvesting period when rainfall totals were higher. A comparison of the observed minimum streamflow totals for periods ranging from 1 to 28 consecutive days before and after clearfelling and burning is shown in Table 15.12. Despite the lower rainfall during the post-harvesting period, minimum flows were between 80% (1 day) and 20% (28 days) higher than observed during the forested period. Even larger gains after clearing may be expected in years with rainfall totals closer to the long-term average. Therefore it is beyond doubt that forest clearing and subsequent burning of slash and undergrowth did have a marked effect on dry season flow, which is in agreement with findings elsewhere in the tropics (Bruijnzeel, 1990; Malmer, 1993).

The impact of harvesting on peak flows was studied by a comparison of regression equations obtained for the pre- and post-harvesting periods. The peak discharge (Q_p) could be related to corresponding rainfall amounts and 15-day API values using the following equation:

$$Q_p = \exp^{a \cdot P + b \cdot API_{15} + c} \tag{15.3}$$

which is similar to the equation used for stormflow volume prediction in the model developed by Schellekens (1992). The regression coefficients for the pre- and post-harvesting periods are shown in Table 15.13 whereas observed peakflows have been

Table 15.12: *Minimum streamflow totals (mm) in the forested Oleolega catchment for periods ranging from 1 to 28 days, and corresponding totals observed after harvesting and burning. Ratios illustrate the relative increase after harvesting.*

Treatment	Period Length [days]								
	1	2	3	5	7	10	14	21	28
	Cummulative streamflow totals [mm]								
Forested (A)	0.11	0.25	0.42	0.69	1.12	1.76	2.51	4.45	6.55
Harvested/burned (B)	0.21	0.42	0.63	1.06	1.55	2.31	3.70	5.83	7.96
Ratio B/A	***1.82***	***1.66***	***1.52***	***1.54***	***1.39***	***1.32***	***1.47***	***1.31***	***1.21***

Table 15.13: *Regression constants and statistics for predictive equations relating peakflows in the Oleolega catchment to rainfall and a 15-day API before and after harvesting and burning.*

Period	a	SD	b	SD	c	SD	CD	n
Pre-harvesting	0.058	0.004	0.008	0.002	-4.023	0.503	0.88	42
Post-harvesting	0.085	0.013	0.017	0.005	-4.049	0.764	0.75	25

plotted against rainfall in Figure 15.7. The pre- and post-harvesting regression lines for an average API_{15} of 45 mm are shown for comparison. The dummy variable technique and F-tests (Kleinbaum and Kupper, 1978) were used to test whether the slopes and intercepts of the two regression lines were significantly different. Differences between the intercepts (c) were not significant. However, the constants a and b of the post-harvesting equation were significantly higher than those of the pre-harvesting equation indicating that peakflows had indeed increased after clearfelling. Again, this finding corresponds with reports from other experiments in the humid tropics where pre-harvesting stormflow was dominated by subsurface flow (Bruijnzeel, 1990; Fritsch, 1992; Malmer, 1993)

15.6.3 Water Quality

Streamflow quality is affected by changes in amounts of dissolved solids as well as of particulate matter (sediment, organic matter) and changes in biological activity (*e.g.* bacteria, algae). Changes in the sediment load and biological activity were not quantified in detail during the present study. What follows below is largely based on visual observations and limited measurements of the suspended load during several storms. Logging activity in the catchment, and the associated disturbance of the soil by the construction of roads, tracks and landings, resulted in a large increase in the sediment load during stormflow events compared to that observed in the undisturbed situation. One landing (L7 in Figure 15.2) had been cut into a slope close to a first order streamhead, with the landing walls steeply sloping towards the stream channel. The access road to this landing was steep, and no sediment traps were constructed along the

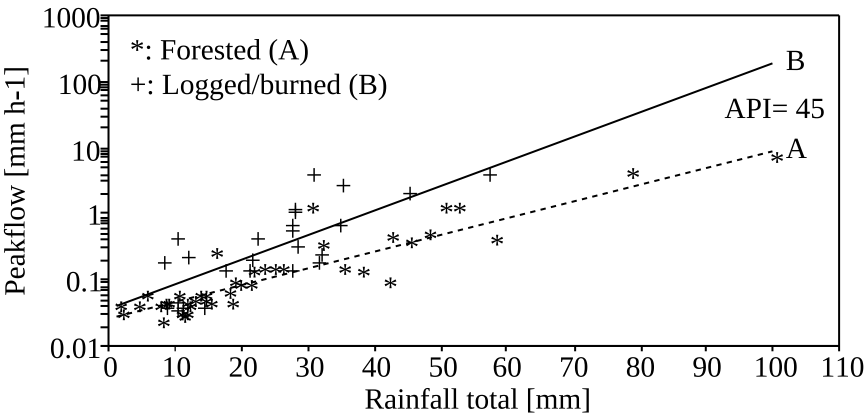


Figure 15.7: *Measured and predicted peak flows (for an average API_{15} of 45) for various storm sizes in pre- and post-harvesting periods in the Oleolega catchment.*

sides. Overland flow from the landing access road and the landing reached the main stream channel within a very short time, thereby producing a sharp, shortlived peak in the hydrograph before the peakflow as a result of the normal catchment response occurred. Gullies formed on this access road within a few weeks, and large amounts of sediment were washed into the stream. As such the peak sediment load was observed during the first runoff peak, rather than during the main peak flow resulting from the overall catchment response to rainfall (Assenberg, 1993). This suggested that most of the sediment in the streamflow may have originated from this particularly ill-constructed landing. Assenberg (1993) examined suspended sediment concentrations in water samples collected during several storms in January and February, 1991, shortly after a number of landings and roads had been constructed, including the one described above. He obtained an erosion rate of 2 tonnes ha^{-1}, which may seem modest in comparison to erosion rates found elsewhere after logging (*e.g.* Douglas *et al*, 1992; Malmer, 1993) but it should be remembered that most of the material came from a limited number of landings and roads, where on-site erosion rates must have been higher.

A large part of the eroded material went into temporary storage, filling pools in the creek and changing its bedding. Flushing of this stored material during large storms may affect the water quality for several years to come (*cf.* Malmer, 1993). In April 1992 gullies with depths up to 40 cm had formed on some of the steeper tracks and roads in the catchment (pers. comm. Dr. J.R.H. Heuch, Fiji Pine Ltd.) and because erosion seemed to remain active in these gullies at least for some time, a semi-permanent decrease in stormflow water quality may be expected as a result of the logging activities. The sediment load under baseflow conditions was not different from that before clearfelling started (Assenberg, 1993).

A lot of these sedimentation problems might have been avoided by a more careful selection of landing locations, as well as of their access roads. Sediment traps were constructed along the main roads in January – February, 1991, which improved the situation. However, some of these traps were spaced too far apart, particularly on steeper sections to prevent overland flow attaining high velocities. As such these traps were filled with sediment after one or two major storms, and their effect correspondingly shortlived.

Nutrient losses associated with the removal of particles of soil and organic matter in the streamflow could not be evaluated since no analyses were carried out on the solids in streamflow samples. However, a comparison between samples containing sediment which were filtered during sampling, and corresponding samples that were not filtered until after arrival in the laboratory, showed that concentrations of PO_4 in the latter were four times higher than those in the former (Table 15.1). This suggested that at least some of the 'available' P in soil was removed from the site absorbed on clay minerals or organic matter in streamflow.

Visual observation of the streamflow revealed that the number of algae in the stream increased after the catchment was deforested. This may have been caused by a combination of higher light inputs to the stream as a result of the removal of the forest canopy, and by higher nutrients concentrations (*e.g.* NO_3). Fresh-water prawns, which were present in the creek before harvesting started, had disappeared after the clearfelling of the forest. The decrease of the prawn population may be attributed to the increased sediment load after harvesting, which destroyed their habitat by filling the pools in the creek.

The impact of harvesting on the chemical composition of streamwater was studied in more detail. Because the quality of the discharge reflects the interactions of vegetation, soil, water and nutrients (Turvey, 1975), a disturbance of the ecosystem will be evident in the chemical composition of the streamflow (Likens *et al.*, 1977). The composition of baseflow differed from that of stormflow and the effects of harvesting on each of these components will therefore be discussed separately.

Chemical Composition of Baseflow

The decrease in nutrient uptake after harvesting and the transfer of large quantities of nutrients to the forest floor, first by cyclone Sina and later by harvesting, which were subsequently released by decomposition and burning of the slash can be expected to have influenced the nutrient concentrations in streamflow from the catchment. Details on the pre- and post-cyclone baseflow composition of the forested catchment have been given in Section 13.7.2. The temporal behaviour of the concentrations of Na, K, Mg, Ca, Cl, NH_4-N + NO_3-N, Mn and total P in baseflow, and patterns of rainfall and streamflow over the entire study period are illustrated in Figure 15.8, whereas average concentrations and corresponding baseflow discharges for various periods are given in Table 15.14. The concentration of Al remained below the detection limit during the whole study period and was therefore not included. The concentrations of PO_4 and total P in streamflow before the burn were also at or below the detection limits, which renders a comparison of the means for the pre-burn periods unreliable and differences were therefore considered not significant. Differences between mean baseflow levels were not significant, except for the post-cyclone period which showed significantly higher amounts of baseflow. Therefore differences between mean ion concentrations may be attributed to the various treatments rather than to differences in discharge. The impact of cyclone Sina on baseflow composition has already been discussed in Section 13.8 and it suffices to say here that the changes in nutrient concentrations in the first month after the event reflected the deposition of sea spray and fresh litter during the cyclone.

Significant changes in baseflow EC, pH, and concentrations of the major ions were

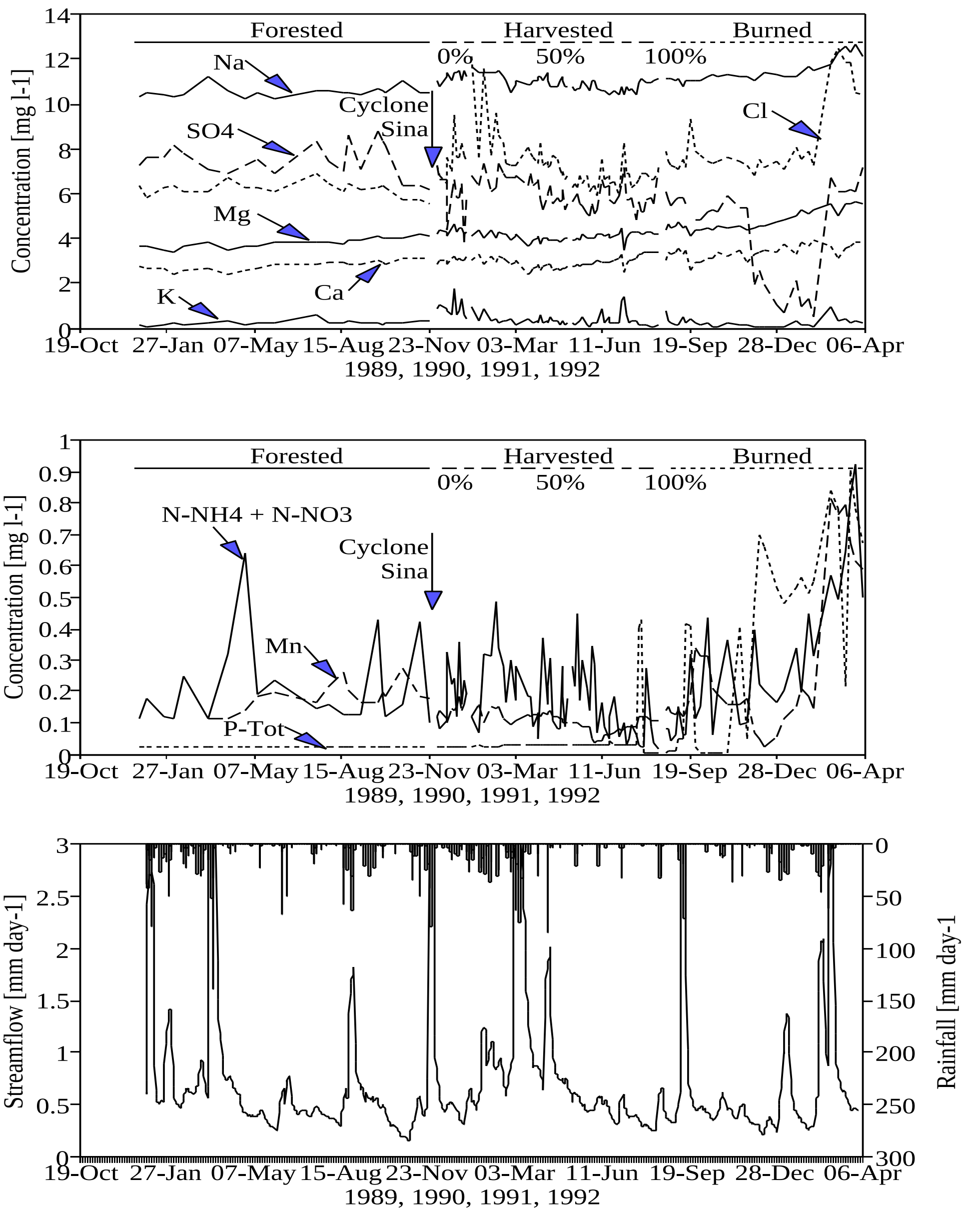


Figure 15.8: *Variations with time in concentrations of Na, K, Ca, Mg, Cl, SO_4, N-NH_4 + N-NO_3, total P, and Mn in baseflow, and corresponding total streamflow (solid line) and rainfall (hanging bars) patterns (bottom figure) before, during, and after clearfelling and burning of the Oleolega catchment.*

Table 15.14: *Average discharge (mm h^{-1}), electrical conductivity (μS cm^{-1}), pH and ion concentrations (mg l^{-1}) in baseflow (Q) from the Oleolega catchment at various stages during the study Significance levels (*Student's t *test) given for differences between mean ion concentrations in the undisturbed state (A) and those after various treatments (B, C, D, E).*

Period	Q	EC	pH	Na	K	Mg	Ca	NH4	Cl	HCO	SO4	NO3	PO4	Si	Fe-T	Mn	N-T	P-T
Pre-cyclone (A), 25 December 1989 - 26 November 1990																		
Average	0.017	91	6.73	10.5	0.24	3.82	2.79	0.22	6.19	36.3	7.47	0.16	0.02	13.7	0.35	0.18	0.08	0.02
SD	0.006	4	0.22	0.2	0.11	0.22	0.21	0.17	0.31	2.2	0.74	0.13	0.01	0.6	0.06	0.04	0.05	0.00
n	21	21	21	21	21	21	21	21	21	21	21	20	20	21	16	16	21	21
Post-cyclone (B), 2 December 1991 - 7 January 1991																		
Average	0.017	94	6.72	11.2	0.89	4.35	3.04	0.21	7.58	38.7	5.94	0.15	0.02	13.8	0.35	0.14	0.15	0.02
SD	0.005	4	0.12	0.2	0.39	0.14	0.12	0.13	0.81	2.3	1.02	0.19	0.01	0.3	0.10	0.03	0.13	0.00
n	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
0-50% harvested (C), 11 January 1991 - 2 May 1991																		
Average	0.031	92	7.10	11.1	0.36	4.02	2.81	0.19	7.85	35.1	6.28	0.27	0.02	14.2	0.32	0.12	0.10	0.02
SD	0.008	5	0.24	0.3	0.19	0.17	0.22	0.11	1.28	4.6	0.57	0.33	0.00	0.4	0.04	0.02	0.06	0.00
n	28	28	28	28	28	28	28	28	28	28	28	27	28	28	28	28	28	28
50-100% harvested (D), 6 May 1991 - 15 August 1991																		
Average	0.018	90	7.13	10.8	0.34	4.13	3.01	0.12	6.66	45.2	5.76	0.18	0.02	13.6	0.22	0.09	0.08	0.03
SD	0.004	3	0.10	0.2	0.33	0.18	0.23	0.12	0.47	2.9	0.58	0.25	0.01	0.4	0.10	0.02	0.11	0.01
n	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
Burned (E), 22 August 1991 - 4 April 1992																		
Average	0.017	97	7.02	11.4	0.24	4.78	3.38	0.27	8.29	49.5	4.45	0.32	0.06	13.0	0.31	0.27	0.28	0.34
SD	0.007	4	0.34	0.5	0.20	0.45	0.32	0.29	1.69	5.8	2.10	0.35	0.05	0.7	0.11	0.23	0.32	0.31
n	31	31	31	31	31	31	31	31	31	31	30	31	31	31	31	31	31	31
Significance of differences between the means																		
A<>B	ns	<***	ns	<***	<***	<***	<***	ns	<***	<***	>***	ns	na	ns	ns	>***	<**	ns
A<>C	<***	ns	<***	<***	<**	<***	ns	ns	<***	ns	>***	ns	na	<***	>**	>***	ns	ns
A<>D	ns	ns	<***	<***	ns	<***	<***	>**	<***	<***	>***	ns	na	ns	>***	>***	ns	ns
A<>E	ns	<***	<***	<***	ns	<***	<***	ns	<***	<***	>***	<**	<***	>***	>*	<*	<***	<***
D<>E	ns	<***	>*	<***	>*	<***	<***	<***	<***	<***	>***	<**	<***	>***	<***	<***	<***	<***

ns: not significant; *: significance level 0.10; **: significance level 0.05; ***: significance level 0.01; na: not applicable

observed shortly after the cyclone event. These again could be linked to the input of sea spray by the cyclone (particularly Na, Cl, Ca, Mg, K), as well as to the release of nutrients (mainly K) by leaching and decomposition of the fresh litter. After this initial flush of nutrients the EC decreased while harvesting progressed, and was not significantly different from that observed during the pre-cyclone calibration period, although the catchment had been logged completely at the end of period D (Table 15.14). Significant increases in baseflow EC were also observed by Malmer (1993) after clear-felling of rain forest on Gleyic Podsols and Orthic Acrisols (62% and 38% areal coverage respectively) in a paired catchment study in Sabah, Malaysia.

The pH of streamflow from the Oleolega catchment was near neutral during harvesting, which was significantly higher than that of the pre-cyclone baseflow from the forested catchment. A possible explanation for this increase is that a reduction in the release of H^+ ions by pine roots to balance nutrient uptake for biomass production may have occurred (Miller, 1984). Since these H^+ ions are important in the weathering process as well (Clayton, 1979), the increase in soil pH_{H2O} (Section 15.4), as well as that of the streamflow, suggested that weathering rates could have slowed down temporarily as a result of the removal of the trees. However, it could also be argued that the increased amounts of water percolating through the soil after clearfelling (Section 15.6.1) would tend to increase the rate of weathering.

The concentrations of Na, Mg, and Cl peaked at the height of the wet season (January – February 1991), which must be attributed to delayed leaching of salts deposited by cyclone Sina because only a small part of the area had been logged by then. This was followed by a gradual decrease and minimum concentrations were reached at the end of the wet season. A slight increase was again observed during the dry season which presumably represented the normal seasonal pattern in the concentrations of these elements, which tend to increase with decreasing baseflow levels (Table 15.15). However, in a paired catchment study in Sabah, Malaysia, Malmer (1993) also observed elevated concentrations of Na and Cl, but not of Mg, in the period between harvesting of rain forest and burning of slash, which suggests that a portion of these ions may also have been released from the slash during harvesting. Concentrations of Ca were highest shortly after cyclone Sina and returned to pre-cyclone levels during the wet season of 1991, after which they increased again during the dry season, possibly as a result of leaching from decomposing litter.

Concentrations of K showed a peak shortly after cyclone Sina but then decreased throughout the harvesting period. This is not surprising in view of the large amounts of foliage that had been deposited during the cyclone event. As logging proceded slowly, the amounts of K released from slash during harvesting were such that these only produced a relatively small increase of the concentration as compared to the pre-cyclone situation. Similar increases in baseflow concentrations of K after harvesting of tropical rain forest in Malaysia were reported by Zulkifli Yusop and Abdul Rahim (1991) and Malmer (1993).

Concentrations of NH_4 and SO_4 decreased after the cyclone event and during harvesting, which may be related to changes in biological processes taking place in the soil. However, the decrease in concentration of NH_4 was more than balanced by an increase in concentration of NO_3, suggesting that a conversion of NH_4 to NO_3 (nitrification) occurred (Robertson, 1989). This was also observed by Parker (1985) in soil solutions after clearfelling (but not burning) rain forest in Costa Rica. Higher NO_3, but unchanged NH_4, concentrations in streamflow were also observed by Swank (1987) after clearfelling mixed hardwood forest near Coweeta, Southeastern USA. Malmer (1993), on the other hand, observed a 20-fold increase in the concentration of NH_4 in baseflow after clearfelling of rain forest in Sabah, Malaysia, whereas no significant changes were observed in those of NO_3, total N and SO_4. Concentrations of total N and Si increased in response to cyclone Sina but not as a result of subsequent harvesting, whereas those of PO_4 and total P did not show any response to cyclone Sina or harvesting and remained below the detection limit for most of the time. Concentrations of Mn also decreased after cyclone Sina and during harvesting of the Oleolega forest. Malmer (1993) observed no change in total N or total P, but significant increases for PO_4 as well as Mn in the streamflow after clearfelling of rainforest.

Concentrations of all elements in baseflow changed significantly after prescribed burning of slash (Table 15.14) in August 1991, but these changes did not occur until three months after the burn. This may be attributed to the low rainfall during this intermediate period, which prevented the transport of any nutrients released by the burn to groundwater. Hence, increased leaching of ions into baseflow did not start until the soil had been wetted thoroughly during the rainy season of 1992 (December). The resulting higher concentrations of Na, Cl, Ca, Mg and HCO_3 caused a significant increase in the baseflow EC (Table 15.14). In the much wetter climate (P= 4000 mm year^{-1}) of Malaysia, Malmer (1993) observed similar increases in baseflow concentrations of Cl, Ca and Mg, but not of Na, immediately after burning of slash.

Concentrations of SO_4 dropped sharply after the burn from a pre-burn average of 5.8 mg l^{-1} to about 1 mg l^{-1} in January 1992 and increased again to pre-burn levels shortly after heavy rainfall in February 1992. It is difficult to explain the behaviour of SO_4 but as its concentration in stream water is known to be strongly influenced by biological sulfur transformations (Swank and Waide, 1987), the decrease may have been caused by changes in biological processes in the soil (activity of Mycorrhizas?) or in stream water after the burn (algae?). Relatively low concentrations of SO_4 were also observed in baseflow from the Ividamu grassland catchment (on average 2.4 mg l^{-1}) where mycorrhizas were presumably absent. Lower concentrations of Si were also observed in baseflow from the Oleolega catchment after the burn, whereas Malmer (1993) observed a significant increase after burning which may be related to leaching from the ash.

Some support for changes in soil biological activity comes from the fact that the decrease in the baseflow concentrations of SO_4 corresponded with a sharp increase in those of total P and PO_4, and with more gradual increases in those of Ca and Mg. In Malaysia, Malmer (1993) did not observe a response in the concentrations of SO_4 after clearfelling and burning of a rainforest catchment.

Changes in the concentrations of Na, K, Cl, total N, NH_4, NO_3 and Mn lagged several weeks behind those of SO_4, PO_4 and total P but showed a similar sharp increase at the height of the wet season of 1992 after replanting had begun. The decrease in concentrations of K to pre-cyclone levels during the wet season of 1992 may be linked to uptake by the rapidly returning grassland vegetation after the burn (Mr. T.T. Rawaqa, pers. comm.) which required large amounts of this nutrient compared to other nutrients (Section 10.4).

The present study ended before nutrient concentrations in baseflow declined to their pre-cyclone levels. However, Hudson *et al.* (1983b), Uhl and Jordan (1984) and Malmer (1993) all observed declines in nutrient concentrations to pre-treatment levels within two years after the treatment, and this may not be very different for those in baseflow from the Oleolega catchment.

Chemical Composition of Stormflow

Stormflow is defined here as a composite of baseflow, channel precipitation and various contributions of water from the hillslope (*cf.* Ward, 1984). As such, its chemical composition can be expected to vary much more with discharge than that of baseflow. Assenberg (1993) observed changes in nutrient concentrations in response to changes in stormflow were not the same for all elements. The EC, and concentrations of Na, Mg, Ca, HCO_3, Si and Mn decreased with increasing stormflow due to dilution with less concentrated waters. However, concentrations of K, NO_3, total P and total N showed the opposite behaviour and increased with discharge, possibly as a result of contributions of water enriched with nutrients after percolating through the canopy, litter layer and topsoil. Very little variation with discharge was observed for Cl, SO_4, PO_4 and Fe. Similar changes in ion concentrations during storms have been reported in catchment studies elsewhere both within and outside the tropics (Hem, 1970; Gregory and Walling, 1973; Likens *et al.*, 1977; Bruijnzeel, 1983a; Malmer, 1993).

Changes in the chemical composition of stormflow may be expected following a cyclone event, harvesting of timber and subsequent burning of slash, due to associated changes in the composition of baseflow (see previous section) and soil moisture on the hillslope (Table 15.10) as a result of changes in leaching and uptake rates in the surface layers (Malmer, 1993). Variations in stormflow with discharge can be expressed with solute rating curves, which usually relate the natural logarithm of stormflow discharge ($\ln Q_s$) to EC, pH or ion concentrations ($[X]$) according to:

$$[X] = a \cdot \ln Q_s + b \tag{15.4}$$

where a and b are regression coefficients (Gregory and Walling, 1973).

Separate solute rating curves were calculated from stormflow samples collected in the periods before harvesting, during harvesting, and after burning. Data for the first stormflow event of the post-burn period were excluded from the regressions as the concentrations of several elements (*e.g.* K, SO_4, Si, Cl) deviated considerably from those of subsequent stormflow events (Figure 15.9). The regression coefficients and their statistics for the respective periods are given in Table 15.15. The scatter in the data

Table 15.15: *Regression constants and statistics of solute rating curves for the forested catchment (n= 43, baseflow data included), harvesting period (n= 167, baseflow data excluded) and post-burn period (n= 59, data for the first storm and baseflow data excluded). EC in $\mu S\ cm^{-1}$, Q_s in $mm\ h^{-1}$ and concentrations in $mg\ l^{-1}$.*

Species	**Forested**					**Logged**					**Burned**				
	a	SE	b	SE	CD	a	SE	b	SE	CD	a	SE	b	SE	CD
EC	-4.465	0.944	75.88	5.25	0.35	-8.276	0.547	70.20	9.57	0.58	-7.638	0.459	74.62	5.96	0.83
pH	-0.084	0.036	6.37	0.20	0.12	-0.112	0.016	6.53	0.28	0.23	-0.198	0.022	6.43	0.29	0.58
Na	-0.507	0.085	8.20	0.47	0.46	-0.826	0.058	7.84	1.01	0.55	-0.681	0.041	8.30	0.54	0.83
K	0.269	0.061	1.53	0.34	0.32	0.113	0.047	1.49	0.83	0.03	0.299	0.039	2.10	0.51	0.51
Mg	-0.230	0.055	2.87	0.31	0.30	-0.505	0.034	2.28	0.59	0.57	-0.570	0.030	2.32	0.39	0.87
Ca	-0.220	0.052	1.89	0.29	0.31	-0.547	0.028	0.86	0.49	0.70	-0.553	0.037	1.09	0.47	0.80
NH4	0.006	0.026	0.22	0.15	0.00	-0.020	0.009	0.14	0.15	0.03	0.003	0.007	0.15	0.09	0.00
Cl	-0.030	0.097	6.03	0.54	0.00	0.451	0.108	10.08	1.89	0.10	1.076	0.112	12.62	1.45	0.62
HCO3	-2.572	1.259	23.07	7.00	0.09	-6.828	0.395	11.05	6.91	0.64	-9.161	0.443	9.73	5.76	0.88
SO4	-0.169	0.145	6.53	0.81	0.03	-0.053	0.069	6.59	1.21	0.00	0.371	0.086	7.65	1.12	0.25
NO3	0.327	0.102	1.57	0.57	0.20	0.475	0.057	2.14	1.00	0.29	1.242	0.099	4.99	1.29	0.73
PO4	0.004	0.006	0.04	0.03	0.01	0.002	0.001	0.03	0.02	0.01	-0.001	0.002	0.02	0.03	0.01
Si	-0.673	0.211	10.42	1.18	0.20	-1.099	0.081	9.27	1.42	0.52	-1.549	0.056	6.89	0.72	0.93
Al	0.017	0.008	0.12	0.05	0.09	0.073	0.011	0.35	0.19	0.22	0.045	0.006	0.24	0.08	0.50
Fe	0.006	0.013	0.36	0.07	0.01	0.006	0.010	0.34	0.18	0.00	-0.013	0.009	0.22	0.11	0.04
Mn	-0.026	0.007	0.06	0.04	0.25	-0.025	0.002	0.01	0.04	0.46	-0.002	0.003	0.02	0.04	0.58
N-tot	0.007	0.010	0.11	0.05	0.01	0.034	0.007	0.23	0.13	0.12	-0.015	0.019	0.26	0.24	0.01
P-tot	0.000	0.000	0.02	0.00	0.01	0.006	0.001	0.04	0.02	0.20	0.049	0.019	0.34	0.25	0.11

was large, partly because of hysteresis effects (*i.e.* differences in ion concentrations at similar discharge during the rising and falling limb of the hydrograph; Gregory and Walling, 1973), and partly because of other factors (*e.g.* time since the cyclone Sina, percentage of area cleared, initial moisture conditions, storm size and intensity), resulting in low to very low coefficients of determination for the regressions (Table 15.15; Turvey, 1975; Malmer, 1993). A selection of solute rating curves for several elements is presented in Figure 15.9. Due to the large scatter of the data and the limited number of stormflow samples collected during the pre-cyclone period differences between rating curves for the respective periods were not statistically significant, with the exception of the post-burn curves for total P and NO_3 which were significantly steeper than corresponding pre-burn curves. Harvesting only had little effect on the rating curves for PO_4 and total P, the concentrations of which remained close to or below the detection limits anyway, suggesting that P released from decomposing litter was retained in the soil. However, concentrations of PO_4 and total P increased greatly after the soil was thoroughly wetted during the wet season following the burn *cf.* Figure 15.8).

Although not statistically significant, the solute rating curves for the other constituents may give a good impression of the changes that occurred in the chemical composition of stormflow after cyclone Sina and harvesting. The pattern of the EC during stormflow reflected that of the major ions (HCO_3, Na, Ca, Mg, Si) of which the concentrations decreased with increasing discharge due to dilution of the baseflow by hillslope contributions and channel precipitation. Changes in the solute ratings of Na, Mg, and HCO_3 as a result of harvesting and subsequent burning were comparable to those shown for Ca in Figure 15.9, with higher concentrations at low discharges and lower concentrations at high discharges during harvesting and after burning than in the forested condition. The effects of burning on the rating curves for these solutes, and also on that for Mn, were smaller than those of harvesting and cyclone Sina combined. Concentrations of these constituents went down during high discharges after harvesting and burning, which suggests that the release of these elements from the litter layer and topsoil during storms was reduced. Concentrations of Mn decreased after harvesting started, but the response to variations in discharge remained similar to that of the forested state as the respective rating curves were roughly parallel (Figure 15.9).

Concentrations of K, NO_3, and SO_4 changed little with storm discharge during harvesting, but larger changes where observed after burning, particularly during the first storm event after the burn (Figure 15.9). Concentrations of Si, and to a lesser extent those of Ca, Mg, Mn and HCO_3, were lower than usual, but recovered again in the subsequent storms (Figure 15.9). The extremely high concentrations of K, SO_4 and Cl that were observed in the first stormflow after the burn indicated that these nutrients had been mobilized by the fire and were now leached from the hillslopes (*cf.* O'Loughlin *et al.*, 1980; Malmer, 1993). Burning had no apparent effect on the concentrations of total N, NO_3, Mn, PO_4, and total P during this first storm, but concentrations of NH_4 dropped below the detection limit.

After clearfelling and burning of rain forest in Malaysia, Malmer (1993) observed higher concentrations of NO_3, NH_4, PO_4, K and Mn in stormflow, whereas those of Si and Fe decreased compared to the forested situation. However, because of the higher biomass involved in this study, the results may not be directly comparable with those presently obtained for the Oleolega catchment.

In spite of the severe disturbance of the Oleolega catchment and the large nutrient inputs to the soil following the burn (*cf.* Section 15.2.2), changes in ion concentrations in streamflow were relatively small, suggesting that most nutrients were retained by the soil, at least during the period of observation. This view is supported by the observed increase in soil nutrient reserves (Table 15.9), which is probably related to a combination of relatively low rainfall following the burn and the relatively high nutrient retention capacity of the soil. Although the various treatments did not result in a deterioration of the chemical quality of the streamflow, a distinct decrease in water quality occurred as a result of increased erosion during and after harvesting (Assenberg, 1993).

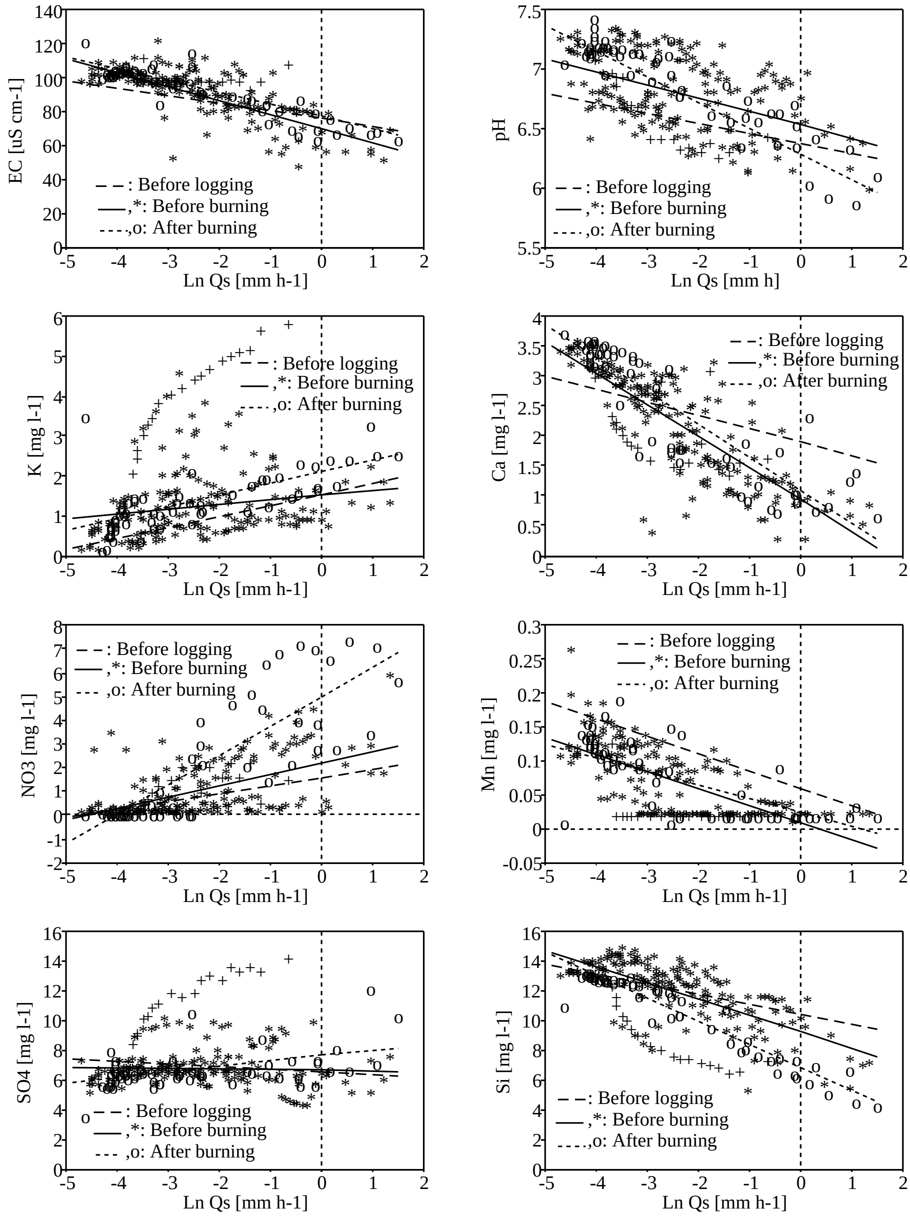


Figure 15.9: *Solute rating curves for the EC, pH and selected elements in stormflow. Data collected during harvesting and after burning included to illustrate the scatter. Data for the first storm after burning (+) not included in the calculation of the post-burn rating curves.*

Table 15.16: *Actual water (Q, in mm) and nutrient exports (kg ha^{-1}) for various periods during the Oleolega catchment experiment, together with the gains in water yield and export of nutrients associated with cyclone Sina, harvesting and burning (also expressed as a percentage of the exports from the forested catchment).*

	Q	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	PO4	Si	Al	Fe-T	Mn	N-T	P-T
Exports from forested catchment (January 4 - November 26, 1990)																	
A	254	26.1	1.08	9.6	7.0	0.53	15.7	88.3	18.5	0.84	0.04	33.7	0.15	0.85	0.43	0.21	0.05
Exports during harvesting (November 27, 1990 - August 15, 1991)																	
B	282	26.6	2.41	9.3	6.0	0.45	22.5	78.3	18.1	3.47	0.06	33.1	0.59	0.97	0.23	0.40	0.10
Exports after burning (August 16, 1991 - April 4, 1992)																	
C	163	17.0	1.69	6.5	4.1	0.44	16.5	59.2	10.0	2.81	0.08	17.6	0.25	0.47	0.34	0.45	0.58
Observed exports during and after harvesting and burning (B+C)																	
D	445	43.5	4.1	15.8	10.2	0.89	39.0	137.5	28.2	6.28	0.14	50.7	0.83	1.45	0.57	0.84	0.68
Predicted exports from the forested catchment for postburn rainfall total																	
E	309	31.9	1.2	11.7	8.5	0.65	19.0	108.3	22.6	0.89	0.05	41.2	0.18	1.04	0.53	0.25	0.06
Gains in water yield and export of nutrients associated with cyclone effects, harvesting and burning																	
D-E	136	11.6	2.9	4.1	1.7	0.24	20.0	29.2	5.6	5.39	0.09	9.5	0.65	0.40	0.03	0.59	0.62
%	44	36	250	35	20	37	105	27	25	603	176	23	361	39	6	238	1072

15.7 Nutrient Exports in Streamflow Associated with Harvesting

Nutrient exports in baseflow from the Oleolega catchment were calculated by combining the concentration data with the corresponding flow volumes. Stormflow samples were collected during each major storm after harvesting started, and the exports during storms could therefore be calculated in a similar fashion.

Only few stormflow samples were collected from October 1991 onwards, and nutrient exports in stormflow until April 1992 were therefore estimated using the post-burn solute rating curves presented in Table 15.15. The resulting nutrient exports from the catchment during the respective periods are summarized in Table 15.16.

The impact of cyclone Sina, harvesting and subsequent burning on nutrient exports was studied by comparing the ‘actual’ exports with those that would have occurred if the catchment had remained under forest. The latter were obtained by simulation using the model developed by Schellekens (1992) to predict streamflow amounts for the forested catchment associated with post-burn rainfall totals (see Section 15.6). Because this model could not accurately predict the quickflow amounts for the extreme rainfall events in March, 1991, the ratio of the observed (82 mm) to the simulated quickflow volume (29 mm) during the calibration period was used to correct the simulated post-cyclone quickflow total (26 mm), resulting in a post-cyclone quickflow total of 75 mm. The simulated baseflow total during the calibration period agreed well with the observed total and no corrections were applied to the simulated post-cyclone baseflow (234 mm). The gain in water yield following clearfelling (0.3 mm day^{-1}) as derived from comparison of observed (cleared conditions) and simulated (forest conditions) water yields, compared well with the reduction in ET following harvesting (0.2–0.4 mm day^{-1}) discussed in Section 15.6, adding confidence to the simulated streamflow total. To estimate nutrient exports under forested conditions with post-burn rainfall totals, the simulated base- and quickflow totals were multiplied with the respective pre-cyclone baseflow and stormflow concentrations.

Nutrient exports from the catchment during and after clearfelling and burning were higher than predicted for the forested catchment. The higher exports of Na, Ca, Mg, NH_4, SO_4, Si, Mn and Fe could be ascribed completely to the higher water yield after harvesting. Exports of total P, PO_4, NO_3, K, and Cl, on the other hand, where much higher than expected from the increase in water yield alone (see bottom row in Table 15.16). These nutrients are intimately connected with biological activity (with the possible exception of Cl, although Khanna and Ulrich (1984) argued that this element could play a significant role in forest nutrient uptake by maintaining electrical neutrality), and were released in large quantities from slash deposited on the forest floor during harvesting (particularly K), and from the ashes following the burn (particularly P, NO_3). However, exports of N, P, K, Ca, Mg and Mn in streamflow (Table 15.16) were small compared to the amounts released from the slash during the burn (Table 15.4), ranging from 0.2% for Mn to 6% for P, indicating that the soil was capable of retaining most of the nutrients released during harvesting at least during the rather dry period of observation.

The export of nutrients in suspended sediment and organic matter was not quantified, and the values given in Table 15.16 should therefore be considered as minimum estimates.

In the next chapter the information presented in the previous chapters on the various nutrient gains and losses will be used to compile an overall nutrient budget for a full rotation cycle of *Pinus caribaea* in the Oleolega catchment.

Chapter 16

Nutrient Balance for the Oleolega Forest

One of the chief objectives of the present study was to evaluate whether pine plantation forestry in Fiji was sustainable under the current management practices, *i.e.* without fertilizing. The preservation of soil fertility is of course a prerequisite for sustained-yield forestry and this implies that nutrient inputs in rainfall and the release of nutrients by weathering of minerals in the rooting zone should match or exceed nutrient exports in streamflow and merchantable timber over a rotation period. If this is not the case, a gradual depletion of soil nutrient reserves will occur during subsequent rotations, eventually leading to nutrient deficiencies and poor growth.

Trends in soil fertility as a result of plantation forestry may be evaluated by solving the mass balance equation for a full rotation period according to:

$$P_x + W_x + F_x = Q_{xs} + Q_{xp} + \Delta S_{xv} + \Delta S_{xl} + \Delta S_{xs} \qquad (16.1)$$

where P_x, W_x and F_x are the amounts of nutrient x supplied by atmospheric deposition, mineral weathering, and biochemical fixation of nutrients in the gaseous phase, respectively, whereas Q_{xs} and Q_{xp} represent exports as solute and particulate matter in streamflow, respectively, and ΔS_{xv}, ΔS_{xl} and ΔS_{xs} the changes in amounts of nutrients stored in the biomass, litter layer and soil reserve, respectively. F_x may be neglected if the mass balance is solved for non-gaseous nutrients, but must be included for N, S and C. Fixation rates for gaseous nutrients were not determined in this study and the mass balance for these elements will inherently be incomplete. Furthermore, exports of nutrients as particulate matter (sediment, organic matter) were not determined either, which will have lead to an underestimation of the exports in streamflow.

Based on the hydrological and hydrochemical data presented earlier in combination with the information on biomass development and soil nutrient reserves, an attempt will now be made to quantify the water and nutrient budgets for the Oleolega catchment over the period of a full rotation (*i.e.* January 1975 – April 1992). Since records of precipitation and streamflow at Oleolega only spanned a 27 month period, several assumptions had to be made to approximate the mean annual rainfall and streamflow totals. Similarly, hydrochemical information was only available for the study period, and the long-term nutrient fluxes in rainfall and streamflow had to be estimated from these data in combination with the derived long-term climatic and hydrological estimates. The approximations were further complicated by uncertainties in the nutrient inputs and outputs during and following the passage of cyclones during the rotation period (six major cyclones between January 1975 and April 1992), and by uncertainties in both the in- and outputs of certain nutrients whose concentrations in water were often below the detection limits (*e.g.* P). The various assumptions and the resulting estimates will be discussed below.

16.1 Nutrient Inputs in Precipitation

The annual rainfall inputs into the catchment were assumed similar to those measured at Nadi Airport from 1975 until 1979 and at Nabou Station from 1980 until 1990. Rainfall data collected for the Oleolega catchment itself were used for 1990, 1991 and part of 1992. Assuming that annual fluctuations in the chemical composition of rain

Table 16.1: *Annual rainfall (mm) and derived atmospheric nutrient inputs (kg ha^{-1}) to the Oleolega catchment over the first rotation period (1975–1990), including harvesting and burning (1991, 1992).*

Year	**P**	**Na**	**K**	**Mg**	**Ca**	**NH4**	**Cl**	**HCO3**	**SO4**	**NO3**	**PO4**	**Si**	**N-T**	**P-T**	**Mn**
1975	2069	13	3.1	1.4	2.0	5.8	25	20	18	3.7	0.5	1.9	3.1	0.41	0.7
1976	1601	10	2.4	1.1	1.6	4.5	20	16	14	2.9	0.4	1.5	2.4	0.32	0.5
1977	1802	11	2.7	1.3	1.8	5.1	22	17	16	3.2	0.5	1.7	2.7	0.36	0.6
1978	1178	7	1.7	0.8	1.2	3.3	14	11	10	2.1	0.3	1.1	1.8	0.24	0.4
1979	1787	11	2.6	1.2	1.7	5.0	22	17	16	3.2	0.5	1.7	2.7	0.36	0.6
1980+	1621	37	3.7	4.6	2.7	4.4	69	13	19	3.0	0.4	1.3	2.1	0.28	0.4
1981+	1932	40	4.2	4.8	3.0	5.4	74	17	23	3.6	0.4	1.6	2.6	0.35	0.6
1982	1973	12	2.9	1.4	1.9	5.6	24	19	17	3.5	0.5	1.9	2.9	0.39	0.6
1983+	1207	35	3.2	4.3	2.3	3.5	65	10	17	2.4	0.3	1.0	1.6	0.21	0.3
1984	1421	9	2.1	1.0	1.4	4.0	17	14	12	2.5	0.4	1.3	2.1	0.28	0.5
1985+	2013	67	5.4	8.2	4.0	5.1	122	14	27	3.6	0.4	1.4	2.2	0.29	0.5
1986	1844	11	2.7	1.3	1.8	5.2	23	18	16	3.3	0.5	1.7	2.8	0.37	0.6
1987	820	5	1.2	0.6	0.8	2.3	10	8	7	1.5	0.2	0.8	1.2	0.16	0.3
1988	1421	9	2.1	1.0	1.4	4.0	17	14	12	2.5	0.4	1.3	2.1	0.28	0.5
1989	2508	15	3.7	1.7	2.5	7.1	31	24	22	4.5	0.6	2.4	3.7	0.50	0.8
1990+	1867	40	4.2	4.8	3.0	5.4	73	17	22	3.6	0.4	1.8	3.1	0.50	0.6
1991	1370	8	2.0	1.0	1.3	3.9	17	80	12	2.5	0.3	1.3	2.0	0.27	0.4
1992*	407	2	0.6	0.3	0.4	1.1	5	24	4	0.7	0.1	0.4	0.6	0.08	0.1
Total	**28842**	**343**	**<50**	**<41**	**<35**	**<81**	**652**	**354**	**<284**	**<52**	**<7.0**	**<26**	**42**	**<5.7**	**<8.9**

+: Years with cyclones; *: January 1 - April 4, 1992

water were small and largely governed by amounts of rainfall, atmospheric nutrient inputs could be quantified by combining the annual rainfall totals with the bulk average chemical composition of rain water at Oleolega (excluding cyclone effects) obtained during the present study. The average concentration of HCO_3 in rainfall at Oleolega was presumably overestimated due to contamination of several water samples (see Section 13.3), and the more realistic estimate for Korokula forest was used instead. The concentrations of Zn and B in rain water (not measured) were estimated by assuming that these nutrients were derived from maritime sources exclusively. Drever (1982) provided average concentrations of Zn and B in sea water, and those in rain water were calculated using Equation 13.1 on the basis of the relative concentrations of Cl in rain and sea water, assuming that fractionation did not occur. Six major cyclones crossed Viti Levu between 1975 and 1992 (two cyclones in 1985) and the atmospheric inputs for these years were increased with the net nutrient input from cyclone Sina, as measured in the Oleolega catchment (*cf.* Table 13.4). The resulting estimates for the rotation period are given in Table 16.1. As the concentrations of K, Ca, Mg, NH_4, SO_4, NO_3, Mn and Total P were often below the detection limits, the inputs of these constituents may have been more or less seriously overestimated. However, the effect will be compensated to a large extent because tall forest vegetation tends to trap aerosols and dust more effectively than the rain water collectors used in the present study (White and Turner, 1970).

16.2 Nutrient Exports in Streamflow

Streamflow records for the Oleolega catchment were not available before 1990. A simple exponential model was developed therefore to relate daily streamflow totals (Q) to daily rainfall totals (P) and a 15-day API, with K in Equation 15.1 set to 0.90 instead of 0.82 to obtain more realistic streamflow outputs for periods without rainfall. Regression analysis was used on data for a 151-day period which included both dry and wet periods (15 February – 15 July 1990), and the following expression was obtained:

$$\ln Q = -0.921(\pm 0.297) + 0.022(\pm 0.002)P + 0.010(\pm 0.001)API_{15}$$
$$\text{n}= 151,\ \text{r}^2 = 0.77 \qquad (16.2)$$

To test whether this simple model could predict long-term streamflow totals accurately, the model was run on an independent 211-day dataset during 1990. The predicted streamflow total for this period was within 1% of the measured streamflow total. However, when the model was applied to the complete data set for 1990, the predicted streamflow total was 7% lower than the measured total due to underestimation of the stormflow associated with the passage of cyclone Rae (March, 1990). Since errors in measurements of stormflow during cyclone events are probably as high as 10% anyway, the model was considered sufficiently accurate for the prediction of annual streamflow totals for the forested catchment. The data presented in Chapters 6 and 7 suggested that evapotranspiration by the pine forests reached a maximum before age six, and remained fairly constant afterwards. As such the current model could presumably provide fairly accurate annual streamflow totals from 1979 onwards.

Annual streamflow totals for the first 4 years after planting, during which ET losses were presumably lower than later in the rotation period, would be underestimated by Equation 16.2. The lower water use of grassland vegetation compared to pine forests is mainly caused by lower dry season transpiration rates as well as lower rainfall interception during the rainy season. To account for the difference in interception losses between the two vegetations, the canopy and litter layer interception models discussed in Sections 6.4.1 and 6.4.2 were run for the daily rainfall data for the years 1975–1990, using the model parameters obtained for Koromani forest (Section 6.4.2) and for Nabou grassland (Section 5.5). The annual difference in interception loss between the two vegetation types ranged from 132 mm in 1987 (a dry year) to 370 mm in 1990 (which was quite wet), and averaged 261 mm. The calculated annual differences in interception loss between grass and pine forest for the years 1975–1978 were added to the annual streamflow totals predicted by Equation 16.2 to obtain a more realistic annual streamflow output for these years. To account for differences in dry season transpiration rates between pines and grassland, the daily streamflow amounts for dry days during the dry seasons of 1975–1978 were increased with the observed difference in daily ET rates from grassland and Koromani forest in 1991 (2.0 mm day^{-1}). This added another 286–382 mm to the predicted streamflow totals for these years. The resulting estimates of annual streamflow totals are given in Table 16.2.

Table 16.2: *Annual streamflow outputs (Q, mm) and nutrient exports (kg ha^{-1}) from the Oleolega catchment over the first rotation period (1975–1990), including harvesting and burning (1991, 1992).*

Year	**Q**	**Na**	**K**	**Mg**	**Ca**	**NH4**	**Cl**	**HCO3**	**SO4**	**NO3**	**PO4**	**Si**	**N-T**	**P-T**	**Mn**
1975	946	98	3.1	35.8	26.2	2.0	58	336	70	2.3	0.2	127	0.7	0.17	1.7
1976	787	82	2.4	29.9	21.8	1.7	49	281	58	1.7	0.1	107	0.6	0.14	1.4
1977	1027	106	3.6	38.8	28.4	2.2	63	362	75	2.7	0.2	138	0.8	0.19	1.8
1978	754	79	2.1	28.7	21.0	1.7	47	272	56	1.5	0.1	103	0.6	0.14	1.4
1979	367	67	2.4	24.3	17.7	1.4	40	226	47	1.8	0.1	86	0.5	0.12	1.1
1980	249	26	1.8	10.1	7.2	0.5	16	90	16	0.8	0.0	33	0.3	0.05	0.4
1981	327	35	2.7	13.2	9.4	0.6	22	117	21	1.2	0.1	43	0.4	0.07	0.5
1982	291	30	1.3	10.9	8.0	0.6	18	100	21	1.0	0.0	38	0.2	0.06	0.5
1983	216	23	1.7	9.0	6.3	0.4	15	80	14	0.6	0.0	29	0.3	0.04	0.3
1984	239	25	1.0	9.0	6.6	0.5	15	83	17	0.7	0.0	32	0.2	0.05	0.4
1985	525	54	4.4	20.6	14.7	1.0	34	180	34	2.4	0.1	68	0.6	0.11	0.7
1986	306	31	1.4	11.5	8.4	0.6	19	105	22	1.1	0.1	40	0.3	0.06	0.5
1987	189	20	0.6	7.2	5.2	0.4	12	67	14	0.4	0.0	25	0.1	0.03	0.3
1988	230	24	0.9	8.7	6.3	0.5	14	80	17	0.7	0.0	31	0.2	0.04	0.4
1989	402	41	2.1	15.0	10.9	0.8	25	136	29	1.7	0.1	52	0.3	0.08	0.7
1990	300	30	1.5	10.0	7.0	0.7	19	95	21	2.3	0.1	40	0.3	0.06	0.4
1991	312	30	2.7	10.5	6.8	0.4	27	92	20	4.6	0.1	36	0.5	0.25	0.3
1992*	86	9	0.9	3.5	2.2	0.3	9	32	5	1.4	0.0	9	0.3	0.42	0.2
Total	**7553**	**810**	**36**	**297**	**214**	**<16**	**500**	**2734**	**557**	**<29**	**<1.4**	**1036**	**<7**	**<2.1**	**<12.9**

*: January 1 - April 4, 1992

The predicted annual streamflow totals over the period 1975–1991 ranged from 189 mm during the dry year of 1987 (P= 820 mm) to 1027 mm in 1977 (P= 1802 mm), with an average of 446(±276) mm. Rainfall during this period averaged 1695(±412) mm, resulting in an average annual ET of 1246(±441) mm, or 3.4(±1.2) mm day^{-1}. Combining this figure with the annual Penman open water evaporation observed at Tulasewa forest in 1990 (1681 mm) would imply an ET/E_0 of 0.74 for the full rotation period. The average ET value is within the range presented by Bruijnzeel (1990, Table 1) for lowland tropical forests, adding confidence to the model predictions. The calculated ET/E_0 ratio is also close to the value of 0.77 calculated by Blackie (1979) from 16 years of rainfall, streamflow and micro-meteorological data collected in a small upland catchment (2400 m a.s.l., 36 ha) in Kenya planted to *Pinus patula* in the first year of data collection.

Because concentrations of several ions in baseflow were different from those in stormflow, separate estimates had to be obtained for the annual totals of the two streamflow components. During the calibration period, stormflow contributions to streamflow were usually observed on days with rainfall inputs higher than 10 mm only. Hence the annual stormflow total was approximated by the sum of the streamflow totals for days with rainfall above this treshold. The result of this rather crude method, when applied to daily rainfall and stormflow data collected in 1990, was within 8% of the actual stormflow total. This suggested that overestimation of the stormflow on days with relatively low rainfall was more or less compensated by the underestimation of stormflow for periods during which stormflow events lasted longer than one day. The annual baseflow total was obtained by subtracting the annual stormflow total from the predicted streamflow total.

Afforestation did not seem to change the concentrations of the most important nutrients (*e.g.* N, P, K, Ca and Mg) in baseflow significantly (Section 13.7.2) and the nutrient export for the years 1975 until 1989 was therefore estimated by combining the annual baseflow totals with the average nutrient concentrations in baseflow from the forested catchment in 1990. To estimate the nutrient output in baseflow for years with cyclones, the baseflow total in the period after the cyclone event until the end of the year was multiplied with the concentrations of the baseflow observed at Oleolega after the passage of cyclone Sina (Table 13.15). The cyclones all occurred in the months January until April, resulting in 8–11 month periods with elevated baseflow concentrations during these years. Afforestation may have affected concentrations in stormflow, but no information was available on this subject and the nutrient outputs via stormflow were therefore approximated using the average stormflow concentrations observed in the forested catchment in 1990. No corrections were made for stormflow outputs in years with cyclones. The calculated nutrient exports in streamflow are presented in Table 16.2. As indicated previously, concentrations of NO_3, PO_4, Total N and Total P were often below the detection limits and estimates for the exports of these nutrients must therefore be considered too high.

The reduction in water yield following the conversion of grassland to pine plantation also reduces corresponding nutrient exports in streamflow. Assuming a reduction of 50% in streamflow after the fifth year after afforestation (Section 9.2) and neglecting any cyclone effects, such 'gains' from reduced water yields could be in the order of 8, 0.8, 11, 92, 124 and 6 kg ha^{-1} for N, P, K, Ca, Mg, and Mn, respectively. However, it is uncertain whether these 'gains' are realistic since the lower soil moisture status and drainage rates below forest vegetation during dry periods may affect weathering rates negatively compared to those below grass vegetation.

16.3 Quantification of the Nutrient Balance

The catchment solute budget was calculated from the information given in the previous sections and the results are presented in Table 16.3. There were considerable losses of Si, Na, SO_4, Mg, Ca, and to a much lesser extent of Mn, which presumably reflects the release of these elements by weathering in excess of the demands from the vegetation. The budgets for K and P, on the other hand, suggested that these elements accumulated in the catchment. However, this may be an artefact of the large difference between inputs and outputs of water, which automatically results in larger inputs than outputs for nutrients with concentrations below the detection limits, because the latter was used as an approximation for the actual concentration in the calculations. No measurements were made of nutrients removed from the catchment with particulate matter in the streamflow and the budget of Table 16.3 must be considered incomplete. These exports will have been negligible for the forested catchment when the sediment load was low even during stormflow events. However, considerable amounts of nutrients will have been removed from the site in suspended particulate matter in stormflow after harvesting started. Some indication for the removal of P with particulate matter can be obtained from the fact that stormflow water samples which had not been filtered in the field showed significantly higher PO_4 levels than corresponding samples that had been filtered during collection (Section 15.6.3). This suggested that some of the available P adsorbed to sediment (clay) particles or organic matter had been released during transport and storage of the samples. For these reasons it may be more realistic to assume a more neutral water budget for P, and possibly also for K.

Nutrient exports in merchantable timber (ΔS_{xv}) from any site in the Nabou forest estate, or from any one of the pine estates in Fiji for that matter, are likely to be highly variable due to the impact of previous cyclone damage and site differences (*e.g.* soil fertility) determining biomass production. At present only stemwood and bark are removed during harvesting, whereas other tree components remain in the field. The nutrient exports associated with harvesting of timber in the Oleolega catchment have already been quantified in Section 15.2.1. However, to study the potential effects of branch and foliage (*i.e.* total tree) removal on the nutrient balance, the exports of nutrients in these components were estimated as well using the appropriate concentration data and ratios of branch mass/stem mass and foliage mass/stem mass observed in Koromani forest. The nutrient exports associated with the removal of the respective components are included in Table 16.3.

Immobilization of nutrients in the litter layer over the rotation period (ΔS_{xl}) could not be determined since no ash layer nutrient data had been collected in burnt grasslands, and neither in the Oleolega catchment at the end of the study (April 4, 1992; 7.5 months after the burn). Although the ash layer contents of P, Zn and Mn immediately after burning the Oleolega catchment in August 1991 (Table 15.4) were higher than corresponding totals in the vegetation – litter complex at the Nabou grassland plot (Table 10.4), subsequent decomposition and leaching of the burnt litter during the wet season of 1992 may well have transferred a large part of these nutrients to the soil. As such, it may be expected that immobilization of nutrients in the litter layer during the rotation period may have been small and ΔS_{xl} was therefore neglected. If the site would not have been burned a large accumulation of nutrients would have been recorded in the litter layer over the period of a rotation. However, since decomposition rates are likely to be higher after harvesting (Gadgil and Gadgil, 1978) than under forested conditions, these nutrients would presumably have become available for use by pine seedlings within the first two years after replanting and must therefore not be considered to be lost permanently.

Some evidence of losses of N due to volatilization during the burn was obtained from a comparison of the amount of N lost from the litter layer during the burn (232 kg ha^{-1}, Table 15.9) and the observed gain in the soil (141 kg ha^{-1}, Table 15.5) after the burn. This suggested that 91 kg ha^{-1}, or 39 % of the total, had been lost through volatilization or in smoke particles.

Whether nutrient depletion at a site occurs depends for a large part on the capacity of the soil to satisfy the nutrient requirements of the forest through weathering of primary minerals. No information has been presented yet on the nutrient input by weathering of soil and rock minerals. The nutrient supply by weathering is usually

Table 16.3: *Quantification of the components of nutrient the mass balance for a full (17.25-year) rotation period in the Oleolega catchment. The budget has been extended to include effects of (a) varying intensities of biomass harvesting and (b) various assumptions on weathering inputs. The maximum possible number of rotations for the worst case scenario was calculated using estimates of available N, K, Mg, and Ca in the soil at the end of the rotation after harvesting and burning and estimates of P reserves (P Bray II) taken from Koromani forest.*

	Na	**K**	**Mg**	**Ca**	**NH4**	**Cl**	**HCO3**	**SO4**	**NO3**	**PO4**	**Si**	**N-T**	**P-T**	**Mn**	**Zn+**	**B+**
Water solute budget [kg ha-1]																
P input	343	<50	<41	<35	<81	652	354	<284	<52	<7.0	<26	42	<5.7	<9	0.1	0.2
Q output	810	36	297	214	<16	500	2734	557	<29	<1.4	1036	<7	<2.1	<13		
P-Q	-467	14	-256	-179	65	152	-2380	-273	23	6	-1010	35	3.6	-4	0.1	0.2
Nutrient exports with particulate matter in streamflow [kg ha-1]																
		?	?	?								?	?	?	?	?
Nutrient exports in biomass components [kg ha-1]																
Stemwood & bark		29	11	23								45	5.3	3	0.6	0.1
Branches*		9	4	9								13	1.3	1	0.1	0.0
Foliage*		24	8	17								51	3.2	4	0.2	0.1
Contribution of nutrients by weathering [kg ha-1]																
Scenario 1: All nutrients provided by weathering																
Weathering input		48	279	228								73	6.2	11	0.8	0.1
Scenario 2: No nutrients provided by weathering																
Weathering input		0	0	0								0	0.0	0	0.0	0.0
Net gains (+) or losses (-) during a rotation period [kg ha-1]																
Scenario 1: All nutrients provided by weathering																
Harvesting of:																
Stemwood & bark		33	12	26								63	4.5	4	0.3	0.1
+ branches		24	8	17								51	3.2	4	0.2	0.1
+ foliage		0	0	0								0	0.0	0	0.0	0.0
Scenario 2: No nutrients provided by weathering																
Harvesting of:																
Stemwood & bark		-15	-267	-202								-10	-1.7	-7	-0.5	0.0
+ branches		-24	-271	-211								-23	-3.0	-8	-0.7	0.0
+ foliage		-48	-279	-228								-73	-6.2	-11	-0.8	-0.1
Soil Nutrient Reserves at the end of the rotation [kg ha-1]																
Available	213	280	2011	1069								110	16			
Predicted number of rotations for scenario 2 and various harvesting intensities																
Stemwood+bark		19	8	5								11	9			
+ branches		12	7	5								5	5			
+ Foliage		6	7	5								2	3			

+: Atmospheric inputs from marine sources exclusively, based on Zn/Cl and B/Cl ratios in seawater (Drever, 1982)
*: Calculated using branch/stem and foliage/stem biomass ratios observed in Koromani forest

approximated by solving the mass balance equation for each of the elements under concern, using data collected in small watersheds (Clayton, 1979). A number of studies have presented estimates of weathering rates obtained with this method (Likens *et al.*, 1977; Clayton, 1979; Johnson *et al.*, 1981; Bruijnzeel, 1983a,b, 1990). However, such wheathering rates were always calculated with the implicit assumption that ΔS_{xs} could be neglected. This is a fair assumption for soils where easily weatherable primary minerals releasing nutrient x are abundant in the soil, or where the vegetation is in a steady state so that the nutrient demands on the soil are low. However, in fast-growing short-rotation plantation forests on less fertile soils the uptake of nutrients for biomass production is likely to exceed the contributions from the atmosphere and perhaps those by weathering at some stage during the rotation, or throughout the rotation period, particularly on poor soils (Lundgren, 1978; Chijioke, 1980; Russell, 1983). Hence under these circumstances ΔS_{xs} cannot be neglected, and should be accounted for. The mass balance approach does not give reliable results for N and P for the following reasons. Nitrogen is a trace element in rocks and the release of this nutrient by weathering can be assumed negligible. Therefore values of N obtained from a mass balance reflect the gains and losses of N through biochemical processes (Robertson, 1989), rather than release by mineral weathering. Determination of the weathering rate for P, and the fraction of total P available for plants, is difficult because of the low mobility of this element (Clayton, 1979). Hence a large proportion of P released by mineral weathering is immobilized in organic soil compounds, inorganic soil compounds (associated with Ca, Fe and Al), and in clay minerals. The amount of P available for plants depends therefore mainly on microbial transformations of P, the ionic activities of Ca, Fe and Al (Clayton, 1979) in the soil solution, and soil pH (Khanna and Ulrich, 1984).

One of the main reasons for studying a pine chronosequence was to obtain information on ΔS_{xs} through comparisons of the available nutrients in the soil of the various plantations. Such information was also obtained by Gholz *et al.* (1985) who observed a general decrease in the soil macronutrient content (N, P, K, Ca and Mg) in an age sequence of slash pine (*Pinus elliottii*, 2–34 years old) on nutrient-poor sandy soils in the coastal plains of Florida. Similarly, Bruijnzeel (1983a) found evidence of soil depletion of Ca, Mg, K and P in a chronosequence (*Agathis dammara*, 7–35 years) planted on volcanic ashes in Java, Indonesia. Although Bruijnzeel (1983a) did take into account the effect of nutrient accumulations in aggrading biomass, the changes in soil nutrient reserves over time were not included in his calculations of the weathering rates. Amounts of nutrients taken up by the vegetation in the studies of Gholz *et al.* (1985) and Bruijnzeel (1983a) were much larger than those taken up by the pine forests in Fiji, partly due to the extended rotation length and partly due to the absence of cyclone disturbance in the former studies. Unfortunately, the high spatial variability in the soils of the Nabou forest estate made it impossible to carry out the study in forests which satisfied both the age (5, 10 and 15 years) and soil criteria (identical chemical and physical properties). As such ΔS_{xs} could not be evaluated properly from the soil nutrient reserves in the study plots, and it remained uncertain what proportion of the nutrients taken up for biomass production was provided by weathering, and what was provided by depletion of soil nutrient reserves.

The capacity of a soil to satisfy the demands for nutrients for biomass production by weathering depends on several factors, including the amount of weatherable minerals, the nature of these minerals, the soil moisture regime, and the soil pH. Weathering may well provide most of the nutrients for biomass production in relatively young soils, such as those in the Tulasewa and Korokula forest plots and in part of the Oleolega catchment, where the zone of active weathering was relatively close to the surface and in reach of the pine roots. However, in older, more deeply weathered soils such as that at Koromani forest and those in other parts of the Oleolega catchment, where primary minerals were less abundant and the pine roots may not reach the zone of active weathering, some portion of the nutrients may have been provided by depletion of soil nutrient reserves. One way to evaluate the possible effects of weathering inputs (W_x) on the nutrient budget is to present budgets for best and worst case scenarios. In the former, all nutrients taken up by the trees are assumed to be provided by weathering, and ΔS_{xs} is therefore zero. In the worst case scenario the nutrients accumulated in the trees are assumed to be supplied from the soil nutrient reserves exclusively, which implies that W_x is zero. Estimations of the net gains or losses for both scenarios are presented in Table 16.3.

If all nutrients for biomass production were provided entirely by weathering, net gains were calculated for all nutrients as long as some portion of the biomass remained at the site. This budget may be appropriate for Ca and Mg which were released in the weathering process, but less so for P, and possibly K and N, which had near neutral or positive hydrochemical budgets (Table 16.3). The losses of Mg, Ca and possibly K, largely reflected the release by weathering and subsequent removal in streamflow, and nutrient deficiencies for these elements are unlikely in view of the large quantities of exchangeable Ca, Mg and K in the soil (Table 4.10). The budget for P may be approximated better by the worst case scenario. The derived loss of P is more critical in view of the large uncertainties in the water budget, the availability of P in the soil at Oleolega, and the fact that enhanced leaching of P during the post-burn phase may have continued for some time after the study ended. Net losses were small for timber removal only, but whole tree removal would result in a sharp increase of these losses due to the high P content of foliage (Tables 11.14–11.16, *cf.* Bruijnzeel and Wiersum, 1985).

Estimations of the maximum possible number of rotations at Oleolega without the necessity for fertilizing can be calculated from the net losses observed over a rotation period and the soil nutrient reserves present at the end of the rotation. If weathering would satisfy the nutrient requirements of the vegetation the number of rotations would be unlimited since the ecosystem would experience net gains of nutrients during each rotation. Because this variant of the budget seems appropriate for Ca and Mg, and possibly also for K, no deficiencies of these elements are likely to occur.

The number of rotations that are possible with the worst case budget ($W_x = 0$) depends strongly on the amount of biomass exported from the site and remaining soil nutrient reserves. The Ca-lactate method for P extraction did not show an increase in soil P after the catchment was burned even though 10.5 kg ha^{-1} had been released from the litter layer (Table 15.4). This suggests that most of the P was stored in a form that could not be extracted with this method and presumably bound to organic matter or less soluble Fe and Al compounds (Dr. V.J.G. Houba, pers. comm.). Assuming that the water budget was correct, and that the long-term available P in the soil of the Oleolega forest may be approximated by the amount of P obtained with the P-Bray II method for the soil of Koromani forest (16 kg ha^{-1} for the upper 60 cm of soil), some 11% of soil P reserves would be lost over a rotation period as a result of timber removal. However, the result for the more realistic neutral hydrochemical budget indicated that P could be depleted already after the third rotation. The soil P content in Oleolega forest may have been higher than that in Koromani forest, and the number of potential rotations may therefore be higher than that suggested in the present budget. On the basis of the calculated hydrochemical budget for K this element would be depleted within fifteen rotations, whereas the neutral budget would reduce the number of rotations to seven. Nitrogen soil reserves were large enough to sustain 16 rotations, without contributions from fixation of N. Hence no N deficiencies are expected in future rotations. No information was obtained on amounts of available Mn in the soil and the corresponding maximum number of rotations could not be calculated. However, because Mn showed a net loss on the basis of the hydrochemical budget, the inputs of Mn by weathering may be sufficient to satisfy the demands by the vegetation. Hydrochemical budgets and soil reserves of Zn and B were not quantified. However, because of the relatively large export of Zn in merchantable timber, this element may become critical in future rotations if the availability in the soil is low.

Some caution should be taken when interpreting these budget estimates. First, the budget does not include amounts of nutrients (*e.g.* P) removed as, or adsorbed to particulate matter produced by surface erosion upon harvesting and burning in streamflow and may therefore be too optimistic. Second, local nutrient deficiencies may occur earlier than predicted for the whole catchment for the following reasons:

- The soil chemical properties showed a large spatial variation and nutrient deficiencies may therefore occur earlier on relatively poor soils in the catchment.
- The disturbance of the litter layer during harvesting had been severe, and slash had not been left *in situ*, but was concentrated around the landings. As such the input of nutrients to the soil as a result of burning showed a very large spatial variation, and deficiencies may occur on locations where the slash and litter layer had been completely removed during harvesting or where leaching could be prolonged due to continued decomposition of slash piles beyond the capacity of the surrounding soils to absorb the surplus supply.

The disturbance of the litter layer, and the deposition of slash are strongly determined by the techniques of harvesting, and changes in these techniques could well minimize these adverse effects (Pearce and Hamilton, 1986).

Part V

Conclusions and Recommendations

Chapter 17

Conclusions

The main objectives of the study were to evaluate changes in the hydrological cycle, with emphasis on changes in water yield, after converting seasonal *Pennisetum polystachyon* grasslands to *Pinus caribaea* plantations, and to determine the sustainability of plantation forestry in SW Viti Levu from a nutrient point of view. Furthermore, several new instruments and techniques were to be tested over longer periods of time in this tropical environment.

Time and financial constraints precluded the monitoring of a single forest over a rotation period (15–20 years) and hydrological, micro-meteorological and ecological studies were therefore carried out between November 1989 and April 1992 in a 'false time series' represented by a grassland plot (Nabou grassland), 6 (Tulasewa forest), 11 (Korokula forest) and 15-year-old (Koromani forest) pine plantations, and a catchment (Oleolega catchment) under 15-year-old pine forest which was logged during the study. The data collected at these sites provided information on the water use and nutrient cycling at several stages of plantation development, as well as on the effects of harvesting and subsequent burning of slash (catchment study). The 'false time series' approach worked well for the quantification of the various components of the water cycles, but proved less satisfactory for the evaluation of changes in the nutrient cycles with forest age because differences in soil properties between the selected study sites affected the components of the nutrient cycles sometimes in such a way that age effects could not always be distinguished from environmental effects.

Interpretation of the results was further complicated by the passage of cyclone Sina over the Fiji group in November 1990, which caused considerable damage to the forest stands and restricted the study periods for pre- and post-cyclone conditions to less than a year each. The occurrence of cyclones, and the amount of damage they afflict to a forest stand are unpredictable and this introduced uncertainties in the long-term predictions of biomass production and nutrient requirements of the plantation forests in Fiji, on top of those originating from spatial and temporal variations in other environmmental variables (particularly soil properties).

It should be stressed that the conclusions listed below apply first to the situation in Fiji, where forest productivity and the intra-system nutrient cycle are strongly influenced by the occasional occurrence of cyclones and soils are relatively fertile compared to the Oxisols and Ultisols which are far more common elsewhere in the tropics (Vitousek and Sanford, 1986). Furthermore, caution should be taken when extrapolating the present conclusions to other plantation species (*e.g. Eucalyptus* sp.) because of possible differences in water use and/or nutrient requirements.

Information on the soils of the study sites was presented in Chapters 3 and 4, whereas effects of harvesting and burning on soil physical and chemical properties have been discussed in Chapter 15. No major improvements in soil physical characteristics were observed as a result of afforestation. Hydraulic conductivities of fire climax grassland and forest soils were generally high in the granular top 20–30 cm, but decreased sharply deeper in the profiles. This will restrict the occurrence of overland flow to only the most extreme rainfall events. However, in areas where the topsoil was removed or severely compacted during harvesting (tracks, roads and landings), overland flow and associated erosion (rill formation) became widespread (Chapter 15). The water holding capacities of the soils were generally sufficiently large to meet the water demands of the forest during dry periods of several weeks, provided that soil depth exceeded 60 cm. Changes in soil chemical properties as a result of afforestation could not be evaluated properly due to the large variation between sites. The soils were moderately fertile with CECs higher than 6 meq 100 g^{-1} and, because roots were observed to penetrate the weathering zone and saprolite, weathering may continue to supply considerable amounts (particularly Mg and Ca) of nutrients for tree growth (Chapter 16).

From the data presented in Chapters 5–8, which deal with changes in the hydrology and micro-meteorology after converting *Pennisetum polystachyon* grasslands to *Pinus caribaea* plantations, the following conclusions can be drawn:

- A decrease in dry season water yield (300–380 mm) will occur within six years after converting grasslands to pine plantations. As indicated in Chapter 9, the main reason for this reduction lies in the fact that the grassland vegetation dies during the dry season, thereby strongly reducing its transpiration losses, whereas transpiration by pine forest continues as long as sufficient moisture is available in the subsoil
- Wet season water yields may also be reduced several years after afforestation for the following reasons:

    1. Evapotranspiration rates (ET) for pine forest are presumably larger than for grass because net radiation above the canopy of the former is higher due to the lower albedo of the pine forest (0.10–0.13 *versus* 0.19 for grass).
    2. Rainfall interception losses from the forest canopy and litter layer (25–30% of rainfall) are higher than those from the vegetation – litter complex in grassland (about 12% of rainfall).

    Therefore the annual decrease in water yield may well be much higher than 400 mm for years with rainfall close to the long-term average (1700 mm). It should be noted here that the impact of afforestation on water use may be somewhat less pronouced in the case that catchments are afforested in which native forest is present in the riparian zone. This riparian forest does not show a seasonal pattern in ET as moisture is never limiting and the dry season water use from the grass and forest vegetation in such a catchment may therefore be somewhat higher than that obtained presently from the grassland plot.
- Pre-cyclone evapotranspiration rates, as determined from micro-meteorological measurements in the 6-year-old Tulasewa forest (Section 7.7) and the catchment water balance method in the 15-year-old Oleolega forest (Section 8.3), indicated that annual ET was somewhat lower in the mature forest (1512 *versus* 1772 mm).

This was presumably caused by reduced transpiration and rainfall interception losses as a result of the lower stocking of the latter (cyclone damage!; see also Chapter 9).

- Forests planted on shallow soils (depth to bedrock < 60 cm) suffered from water stress during the dry season (Section 8.3). This induced high litterfall (Section 12.3.1) and limited forest productivity (Section 11.5.1).
- Damage afflicted to the pine forests by Cyclone Sina resulted in a more or less permanent decrease in ET for Tulasewa forest where 40% of the trees were destroyed, and more temporary decreases (presumably during 1–2 years of canopy recovery) at the Korokula and Koromani sites where trees were only defoliated. The soil moisture depletion technique suggested a 32% reduction in transpiration in the post-cyclone dry season at the Tulasewa plot. Comparison of pre- and post-cyclone dry season ET_{sm} was complicated (particularly for the Korokula site) by the difference in rainfall between the periods but indicated an 8% reduction at Koromani forest where rapid regrowth of foliage was observed after cyclone Sina (Section 11.3.6). Post-cyclone wet season interception losses from the canopy and litter layer at the Tulasewa (23% of rainfall) and Korokula (21% of rainfall) sites were lower than those observed during the pre-cyclone wet season (29 and 30% of rainfall, respectively).
- Harvesting of the mature pine forest and subsequent burning of slash in the Oleolega catchment increased water yield by about 50% during a rather dry period. Even higher gains in water yield might therefore be expected in years with rainfall closer to the long-term average. Increases were observed in both minimum and peak flows (Chapter 15).

In combination with data on nutrient inputs via atmospheric sources and losses in drainage water (Chapter 13) the information on forest productivity, litter production and decomposition presented in Chapters 10 – 12 has been used to compile pre- and post-cyclone nutrient budgets for the respective forest sites (Chapter 14). In addition, a budget for the Oleolega catchment over a full rotation (January 1975 – April 1992) has been given in Chapter 16. The following conclusions can be drawn from the information presented in these chapters:

- Afforestation resulted in an increase in above-ground biomass from about 8 t ha^{-1} for grassland at the end of the wet season to about 150 t ha^{-1} for a mature (cyclone damaged) pine forest. The corresponding nutrien accumulation rate was highest around age six just before canopy closure due to the rapid development of the nutrient-rich crown, whereas it slowed down after canopy closure when nutrient accumulation occurred mainly in nutrient-poor woody tissue.
- Amounts of pre-cyclone litterfall generally increased with forest age, but also showed a dependency on stand density and soil water holding capacity. Litterfall constituted the main pathway for the return of nutrients from the living biomass to the forest floor, with the exception of K, which was returned mainly in canopy wash. Amounts of Litterfall and associated nutrient returns to the forest floor during cyclone Sina were up to three times larger than annual pre-cyclone values. Because cyclones are a regular phenomenon in Fiji nutrient

returns to the forest floor in cyclone litterfall may be as important as those in periods between cyclones.

- The pre-cyclone mass of the litter layer increased from about 7 t ha^{-1} for grassland at the end of the wet season to 13.5 t ha^{-1} for mature pine forest at Koromani. Immobilization of nutrients in the pre-cyclone litter layer occurred but the rates of accumulation were low compared to the available amounts of nutrients in the soil (typically less than 1%). The post-cyclone litter layer mass and nutrient content reflected the large amount of litter and associated nutrients added to the forest floor during cyclone Sina.
- Needle decomposition in the forest plots was fairly rapid with 43–48% mass loss in the first year. Relatively large fractions of K (over 60%) and P (20–50%) in needle litter were released within three months after incubation, whereas rates of release of N, Ca and Mg were much lower with less than 50% being released after a year.
- Despite low atmospheric nutrient inputs, positive (*i.e.* accumulation) or near neutral hydrochemical budgets were calculated for N, P, K and Mn. Budgets for Mg, and to a lesser extent Ca (only at the Korokula and Oleolega sites), were negative due to relatively high exports of these nutrients in drainage and streamflow, suggesting that these ions were released by weathering in excess of the requirements of the vegetation.
- Nutrient losses associated with harvesting and burning in the Oleolega catchment were relatively low, with losses in merchantable timber removed from the site exceeding those by leaching in streamflow. A large proportion of the nutrients that were released from the slash, initially through decomposition and later during the burn, were retained by the soil and losses by leaching in streamflow mainly concerned P, N and K. The water quality decreased markedly during storms as a result of increased sediment loads due to erosion of places with severely disturbed soil in the catchment (log landings, extraction roads).
- The nutrient budget presented for a full rotation period in the Oleolega catchment indicated that for a 'worst case' scenario (no nutrient inputs by weathering) and removal of merchantable timber only as opposed to whole tree removal, no deficiencies of N, P, K, Ca, Mg or Mn were likely to occur within 5 rotations. However, if whole tree harvesting would be practised N and P deficiencies could be expected by the third rotation. Therefore the main threat to the productivity of pine plantation forests in Fiji is cyclone damage.
- The productivity of second rotation forest in the Oleolega catchment will be lower than that of the first rotation due to the increase in area (from 2% to 10%) with severely compacted soils (Section 15.1.2), although differences in cyclone damage between rotations may mask the effect.

As for the testing of commonly used measurement techniques in this humid tropical environment, several micro-meteorological methods were used to determine forest evapotranspiration rates. The temperature fluctuation energy balance method, with which half-hourly ET rates were obtained from measurements of above-canopy temperature at a single level in combination with estimates of available radiant energy, gave results that were comparable to those obtained with the more conventional (and data demanding) Bowen Ratio Energy Balance method (Section 7.6.2). Using the results of the former method to derive relationships between various climatic and soil moisture variables on the one hand, and the surface resistance parameter on the other hand, enabled the calculation of long-term ET rates with the Penman-Monteith method from routine measurements of micro-meteorological parameters. This approach seems quite promising for use in developing tropical countries in view of the simple and relatively cheap micro-meteorological set-up that is required for its application.

The Didcot capacitance soil moisture probe provided fairly accurate measurements of volumetric soil moisture content, in spite of the high volumetric moisture contents of the soil (often higher than 35%). Reliable estimates of the rates of ET during dry periods were derived from the soil moisture depletion method using soil moisture data collected in the Nabou grassland . However, the impossibility to install access tubes beyond the maximum depth of pine roots prevented accurate determinations of transpiration rates in the forest plots in this way.

Finally, with respect to the testing of existing catchment hydrological models in the study environment, climatic and streamflow data collected at the Tulasewa and Oleolega sites, respectively, were used to test the TOPOG model (O'Loughlin *et al.*, 1989) developed by the Cooperative Research Centre for Catchment Hydrology of the CSIRO Division of Water Resources, Canberra, during a two-week visit by the author to the Canberra laboratory in October 1991. The results looked promising but further work is necessary as most of the data had not been processed at that time. Unfortunately, processing of data and writing of this dissertation left no time for further applications.

Chapter 18

Recommendations

18.1 Research Targets

The following aspects of plantation forestry in SW Viti Levu need further attention:

1. One of the main gaps in our knowledge concerns the water use of unproductive (seasonal) grasslands in the tropics. The present study has partly filled this gap by determining the water use during part of the dormant (dry) season. However, the seasonal variation in hydrological, plant physiological and micro-meteorological parameters (*e.g.* interception characteristics, albedo, net radiation, stomatal resistance) could not be quantified due to time and material constraints. Since an increasingly larger area in the tropics will be covered with grassland as a result of deforestation, and the demand for forest products is still increasing, such areas may be targeted for reafforestation in the future (Evans, 1992). A study which would improve our understanding of the hydrology and micro-meteorology of these grasslands seems justified therefore.

2. Whether plantation forestry is sustainable depends for a large part on the capability of the soil to supply the nutrients required for biomass production in subsequent rotations. However, very little is known on the amounts of nutrients supplied by weathering in tropical soils. Published estimates of weathering rates that are based on nutrient input – output budgets for forested catchments may well be overestimates as the depletion of soil nutrients with time has usually not been taken into account. To properly evaluate weathering inputs within the context of plantation forestry on soil nutrient reserves, soil surveys should be carried out periodically, preferably in permanents sample plots. On the basis of the present findings nutrient deficiencies are not expected for the plantations in the Nabou estate. However, to determine the risks for other estates on geologically different substrates, the pedological studies conducted earlier by the Fiji Pine Commission and the University of the South Pacific should be reviewed in this respect.

3. Additional research is necessary to determine which methods commonly used for the determination of 'available' nutrients in the soil accurately describe the response of tree growth.

4. Fairly reliable estimates of atmospheric nutrient inputs for periods without cyclones have been presented in Chapter 13. However, large uncertainties exist with respect to the magnitude of inputs during cyclone events. It is therefore recommended that the rainfall collected at a selected number of rainfall stations (including coastal and inland stations) of the Fiji Meteorological Service during such events be analysed to obtain more information on the spatial variablility and the magnitude of such inputs.

5. Nutrient losses in suspended sediment during and after harvesting were not quantified in the present study and further research is necessary.

6. The testing of the TOPOG model (O'Loughlin *et al.*, 1989) on preliminary data collected in the Oleolega catchment indicated that the model may well be used to identify areas where plantation forest would be prone to moisture stress, or areas sensitive to erosion during and after harvesting. Furthermore, it may be used to predict the effects of land-use conversion on the hydrology of a given area and could therefore be an excellent tool in the planning of forestry activities (selection of future plantation areas, planning of locations of roads and landings at the end of a rotation). However, further testing of the model and quantification of the model parameters with respect to the situation in Fiji is necessary.

18.2 Forest Management

Based on the information presented in this dissertation, the following recommendations can be made:

- Grassland catchments which are presently used for the water supply of urban or rural areas should preferably not be converted to plantation forest for the following reasons:

  1. Afforestation of grassland catchments will lead to reduced water yields to such an extent that water shortages are likely to occur during dry periods, as has been the case with the Varaciva catchment (Kammer and raj, 1979).

  2. Unless exceptional care is taken during harvesting (*e.g.* sky line or manual extraction of logs), the construction of roads and landings associated with the removal of merchantable will almost certainly lead to increased erosion and therefore higher sediment loads in streamflow during storm events. This reduces the quality of the water and creates problems for the water supply to downstream villages.

  It is recommended therefore that water authorities participate in the planning of afforestation projects in such grassland areas.

- To minimize the extreme spatial heterogeneity in amounts of logging debris during harvesting, trees should be stripped from their crowns immediately after felling and the slash should be left *in situ* as a mulch. From a soil conservation point of view burning of the slash should be avoided for the following reasons:

  - The slash and litter layer protect the soil from direct raindrop impact, thereby reducing chances of physical degradation of the topsoil to a large extent.

  - Nutrient release from the slash and litter layer by decomposition are gradual and this will prevent the losses via leaching in streamflow (particularly K, P, N) and volatilization (N), as were observed after the burn in the Oleolega catchment. Furthermore, newly planted pines may profit from the slow release of nutrients from the mulch

  Site accessability for planting could be improved by the cutting of large pieces of woody debris (such as tree tops, large branches) into small pieces when the crowns are stripped at the stump. This would have the additional advantage of speeding up the decomposition of these components, thereby reducing the fuel load and thus subsequent fire hazard. The presence of a mulch cover after planting has the additional advantage that evaporation from the wet soil is reduced, although this may partly be compensated by higher rainfall interception losses from the litter. This would reduce the chance of water stress occurring shortly after planting. When planting and mulching is done immediately after harvesting, the competition between the young pines and the returning grassland vegetation may not be too large. A rapid return of the grasland vegetation was observed after burning in the Oleolega catchment and the effect of burning with respect to weed suppression may therefore be limited anyway.

- Since nutrient deficiencies are not likely to occur in subsequent rotations in the Oleolega forest, the largest threat to the sustainability of the plantation forests comes from a degradation of the physical properties of the soil (depth, water holding capacity, permeability) by compaction and erosion. This may lead to water stress as well as problems with root development (Van der Weert, 1974) Roads and landings should therefore preferably be located on the ridges where the soil is already shallow, and cutting of roads in steep hillslopes should be avoided as much as possible to avoid soil degradation which may also affect adjacent, relatively undisturbed, areas downhill.

- Forests should preferably be planted on soils with depths over 60 cm since the productivity may otherwise be affected by frequent water stress and possibly also by problems with root development.

- Soils were observed to remain moist throughout the dry season after harvesting, and planting may therefore start after the first rainy period at the end of the dry season without the risk of moisture stress for the saplings.

Chapter 19

Summary

The destruction of natural forest, presumably by fire, shifting cultivation and overgrazing in the previous century has lead to a fire-climax grassland vegetation cover in West Viti Levu, Fiji (Twyford and Wright, 1965), where rainfall exhibits a seasonal pattern with an annual total of about 1800 mm. To meet increasing demands for pulpwood on the world market and local demands for timber, as well as to provide business opportunities for the land owners, extensive areas of these *Pennisetum polystachyon* grasslands have been afforested to *Pinus caribaea* since the 1960s by the Fiji Pine Commission. This afforestation allegedly led to reduced water yields from catchments in the North of Viti Levu within six years after planting (Kammer and Raj, 1979) in turn producing shortages in the urban water supply during dry periods. When these forests were harvested in the 1980s, a deterioration of the water quality was observed due to enhanced erosion leading to high suspended sediment loads during rainstorms. In addition, nutrient deficiencies (shoots without needles) became apparent in second rotation forests in the 1980s, which raised the question if plantation forestry was sustainable at all without the application of fertilizers. With respect to these issues, a study was initiated in 1989 as part of a collaboration between the Free University of Amsterdam and the Fiji Pine Commission (now Fiji Pine Ltd.), funded by the Netherlands Foundation for the Advancement of Tropical Research (WOTRO, grant no. W84-295) with the following objectives:

- to quantify any changes in the hydrological cycle as a result of converting *Pennisetum polystachyon* grasslands to *Pinus caribaea* plantations
- to evaluate the sustainability of pine plantation forestry in SW Viti Levu from a nutrient point of view
- to study the impact of harvesting and subsequent burning of slash on catchment water yield and quality, as well as on soil physical and chemical properties

Since it was not feasible to monitor a single plantation over a full rotation period (16–20 years), the 'false time series' approach (Hase and Fölster, 1982; Bruijnzeel, 1983a; Gholz *et al.*, 1985) was used to study the water and nutrient dynamics at several stages of plantation development. Hydrological, micro-meteorological and ecological studies were carried out between November 1989 and October 1991 in a grassland plot at Nabou, in three forest plots carrying six, eleven and fifteen year old forest (at Tulasewa, Korokula and Koromani, respectively). In addition, hydrological

Table 19.1: *Characteristics of the vegetation at the respective sites. Biomass and CAI data are for the pre-cyclone period.*

Research Site	Age [yr]	Stocking [ha-1]	Dbhob [m]	h [m]	BA [m2 ha-1]	Living biomass [t ha-1]	CAI(1990) [t ha-1 yr-1]
Nabou grassland	0	na	na	na	na	8	na
Tulasewa forest	6	825	0.16	11.6	18.1	70	22.5
Korokula forest	11	822	0.20	14.7	27.5	111	7.6
Koromani forest	15	621	0.25	17.5	31.6	148	9.6
Oleolega forest	15	459	0.25	18.3	15.8	109*	-

Dbhob: diameter at breast height (1.35 m); h: tree height; BA: Basal area; CAI: Current annual increment
na: Not applicable; *: Biomass of riparian forest not included

measurements were made between January 4, 1990, and April 5, 1991, in the Oleolega catchment which had been planted to pines in 1975 and was logged and burned in 1991 as a salvage operation after the forest had been severely damaged by cyclone Sina in November, 1990. This cyclone had a large impact on both the hydrological and nutrient cycles. The sites were all located in the Nabou Forest Estate (Figure 2.2) in SW Viti Levu, which was established in 1975. Some information on vegetation characteristics of the grassland and forest sites are presented in Table 19.1.

The *Pennisetum polystachyon* grassland vegetation is highly seasonal, with active growth during the wet season (November – April) and low productivity during the dry season. Since it is during the dry season that water shortages as a result of afforestation become acute, measurements at the Nabou grassland site were carried out mainly during the dry season of 1991. The results of the studies made at the respective sites will be summarized below.

Soil Physical and Chemical Aspects

The grassland and forest soils differed markedly in their physical and chemical characteristics, which could be attributed to differences in parent rock (dacites, andesites, and basalt–diabase), weathering processes and the degree of erosion. The forest soils were classified as Mollisols (Nabou grassland, Tulasewa and Korokula forests) and Oxisols (Koromani forest), of which the fertility was moderate (Koromani forests) to good (Tulasewa forest). Soil properties in the Oleolega catchment were highly variable but two major soil groups could be distinguished based on soil texture, depth and colour, which were associated with changes in the underlying parent rock (dacite–trachite, basalt–diabase). The soil in Korokula was shallow (bedrock between 30 and 80 cm) and still contained fairly large amounts of strongly weathered primary minerals, suggesting that this soil was relatively young. Weathering had progressed somewhat further in the soil of Tulasewa forest (bedrock at 80–150 cm), whereas the soil at Koromani forest (bedrock deeper than 150 cm) was in an advanced state of weathering and was considered to be relatively old. The soils in the Oleolega catchment ranged from those similar to that at Korokula forest (mainly on ridges in the north of the catchment on dacite rock) to that at Koromani forest (on hillsopes in the south of the catchment on basalt–diabase rock).

The soils were well-drained, with generally high hydraulic conductivities in the topsoil, but much lower values in the subsoil. Bulk densities ranged from 0.97 to 1.16

g cm^{-3} in topsoil, and increased to values between 1.1 and 1.5 g cm^{-3} in subsoil. Porosities were relatively high, both in topsoil (46–51%) and subsoil (39–64%). Data collected in the grassland and forest plots and in the Oleolega catchment did not suggest that any major changes in soil physical properties had occurred as a result of afforestation because differences in bulk density and saturated hydraulic conductivity between soils under forest were as large as those between forest and grassland soils (Tables 4.2 and 4.3). Some evidence was found which suggested that the higher root activity of pines did improve the soil structure of subsoil below the rooting zone of grass (0–80 cm), contrary to the findings of Latham (1983) and Bayliss-Smith (1983) who observed improvements in topsoil after afforestation with pines in Fiji. It must be noted that the evaluation of changes as a result of afforestation from a comparison of sites remains difficult due to the large spatial variation in properties of the soils in Fiji.

The water holding capacity (59–123 mm) of the shallow (0.3–0.8 m) soil in Korokula forest was insufficient to supply moisture for sustained transpiration by the pines during a dry period in April–May 1990 and water stress, as indicated by high litterfall, was observed. No water stress was observed during the same period in the other forests where the soils were deeper (1–2 m) and therefore had a higher storage of soil moisture (>150 mm). This illustrates the importance of soil depth in determining whether a particular forest is likely to suffer from water stress or not under the prevailing climatic conditions. Frequent water stress may be expected on soils with depths less than 0.5 m, and the forest productivity on such sites will be low, regardless of the nutrient content of the soil.

Significant changes in soil physical properties were observed following harvesting and burning in the Oleolega catchment. The mean bulk density of the topsoil increased from 1.07 to 1.13–1.17 g cm^{-3}, but the increase was not such that it fell outside the normal range observed in the forest study sites (0.99–1.16 g cm^{-3}). This coincided with a drop in the saturated hydraulic conductivity of the topsoil, with the largest decreases being observed on the landing and road surfaces. However, reductions in hydraulic conductivity in areas that had been harvested and burned, but not disturbed otherwise by heavy machinery, were not so large that overland flow occurred or reductions in the growth of second rotation forest were to be expected. Overland flow and associated erosion was observed on the severely compacted surfaces of landings and roads where the removal of topsoil often had decreased the soil depth to such an extent that the C-horizon or bedrock became exposed. The productivity of second rotation forest planted on these areas may be impaired for the following reasons:

- The soil depth, and therefore the water holding capacity was reduced. Pines planted on these surfaces are therefore likely to experience water stress during dry periods
- The compaction and the massive structure of the soil may have a detrimental effect on the root development of the pines (Van der Weert, 1974)

The fertility of the soils was moderate (Koromani forest) to good, with the highest nutrient contents in the soil of Korokula forest. The Bray-II method (Bray and Kurtz, 1945) and the Ca-lactate extraction methods for the determination of soil 'available' P produced widely differing estimates. The results of the latter (3.5–5 kg ha^{-1}) seemed unrealistically low in view of the amounts already accumulated in the trees and litter layer. The Bray-II method was thought to provide more realistic estimates (24–164 kg ha^{-1}).

Grassland *versus* Forest Water Use

Estimates of evapotranspiration from grassland for selected dry periods (n= 59 days) during the dry season of 1991 were derived from soil moisture depletion measurements with a Didcot soil moisture capacitance probe. Surface resistances (r_s) for grass were calculated for these periods by inserting the ET_{sm} values and micro-meteorological data collected above the grass in the inverted Penman-Monteith equation. These surface resistances were in turn related to the LAI of grass via a simple linear regression model. The latter equation was subsequently used to calculate the average daily ET_{pm} rate for a 131-day period during which the grass was dead, resulting in a value of 1.0(±0.3) mm day^{-1}. The corresponding Penman open water evaporation (E_0) was 3.7 mm day^{-1} resulting in a very low ET/E_0 ratio of 0.26. The same approach for the derivation of r_s could not be used in the forest plots where ET_{sm} values were underestimated because soil moisture measurements could not be made down to depths below the rooting zone.

Therefore, a combination of various micro-meteorological techniques (Bowen Ratio and Temperature Fluctuation Energy Balance methods and Penman-Monteith method) was used for the determination of forest ET on a half-hourly basis in the Tulasewa and Koromani forest plots, whereas the water balance method was used to derive estimates of wet and dry season ET for the forested Oleolega catchment. As indicated earlier, the study sites were struck by cyclone Sina in November 1990. This resulted in large changes in foliar biomass and, indeed, total forest biomass in the case of Tulasewa forest where the stocking decreased overnight from 835 to 489 trees ha^{-1}. Needless to say that pre- and post-cyclone ET rates differed rather strongly. Calculated pre-cyclone dry season ET rates ranged from 3.3 mm day^{-1} for the mature pine forest in the Oleolega catchment to 4.0 mm day^{-1} for the young forest at Tulasewa. Corresponding Penman open water evaporation rates (E_0) were 3.8 and 3.5 mm day^{-1}, resulting in ET/E_0 ratios of 0.9 and 1.1, respectively. After Koromani forest had been defoliated by cyclone Sina, a relatively low ET value of 3.0 mm day^{-1} was derived for the dry season of 1991, in spite of a higher E_0 (4.2 mm day^{-1}) compared to those calculated for the other sites a year earlier. This resulted in the relatively low dry season ET/E_0 ratio of 0.7 for mature, cyclone damaged pine forest. The low post-cyclone ET in Tulasewa forest resulted in high soil moisture levels throughout the dry season.

Micro-meteorological measurements above grass and pine forest indicated that the albedo decreased from 0.18 for grass to 0.10–0.13 for pine forest, resulting in higher net radiation totals above the latter. Soil heat flux totals were low in a dense grass stand at Oleolega, but even lower values were observed in the pine stands. Energy storage within the pine canopy and biomass was low. These observations indicate that the available energy for partitioning over the latent and sensible heat fluxes is higher above pine forest than above grass. Afforestation also caused an increase in the aerodynamic roughness of the vegetation, resulting in a decrease of the aerodynamic roughness from 31 s m^{-1} for grass to about 14 s m^{-1} for pine forest. These changes suggest that the forest ET will be higher than the grassland ET during the wet season as well. Observed diurnal ranges of temperature and humidity above grass were larger than above pine forest.

Rainfall Interception losses in the canopies and litter layers of the respective forest sites were estimated from above- and below-canopy/litter layer measurements of rainfall. Interception losses in the forest chronosequence varied little, ranging from 26% of total rainfall in the 15-year-old Koromani forest to 29% in the 11-year-old Korokula forest, of which some 10% was lost in the litter layer. The (modelled) interception loss for grassland (Gash's analytical model and litter layer interception model developed in this study; Section 5.5) was much lower at 12% of total rainfall. As rainfall interception in the 6-year-old stand at Tulasewa amounted to 27%, this suggested that interception losses increased by some 14% of total rainfall in the period between planting and canopy closure around age six. Not surprising, interception losses decreased by several percent as a result of damage afflicted by cyclone Sina (gap formation, defoliation). These changes were presumably only temporary in the older forests where the stocking had not changed to a large extent. However, a permanent decrease may be expected for the stand at Tulasewa where 40% of the trees were destroyed.

Comparison of dry season evapotranspiration losses from *Pennisetum polystachyon* grassland and from *Pinus caribaea* plantations suggested an increase in these losses of 300–400 mm, and therefore corresponding decreases in water yield, within the first six years after afforestation. Evapotranspiration losses remained fairly constant thereafter. The change in the dry season water use after afforestation must be attributed to differences in transpiration between the (then largely dormant) grassland vegetation and the actively growing pines. Differences in rainfall interception characteristics are less important during the dry season but will play a significant role during the wet season.

Water balance measurements in the Oleolega catchment indicated that a modest reduction in ET (7–14%) occurred during a rather dry period following harvesting of the mature pine forest and subsequent burning of the slash. However, this reduction was sufficient to produce a 51% increase in water yield compared to that modelled for the forested catchment using post-harvesting rainfall data as input (Chapter 15). Harvesting of the forest and subsequent burning of slash increased minimum flows, which were 20–80% higher than those measured a year earlier for the forested catchment, as well as peak flow levels. Because the period after harvesting was much drier than usual (887 mm *versus* 1418 mm), larger reductions in ET, and therefore higher increases in the water yield may be expected with rainfall conditions closer to the long-term average.

The present study indicates that afforestation of areas under seasonal grass cover in SW Viti Levu does lead to reduced water yields during the dry season due to increased transpiration losses, and presumably during the wet season as well due to differences in interception characteristics. In turn, harvesting of the forest at the end of the rotation followed by burning results in increased water yields. Since the grassland vegetation returned within a few months after burning, and the disturbance to the soil associated with the logging activities did not result in the occurrence of overland flow on a large scale, the water use by the regenerating vegetation shortly after harvesting may be fairly similar to that of the catchment before afforestation.

Nutrient Cycling

All study forests were accumulating biomass at a high rate during the pre-cyclone period, with the above-ground tree and undergrowth biomass increasing from about 8 t ha^{-1} in grassland to 150 t ha^{-1} in 15-year-old forest (Table 19.1). The corresponding nutrient requirements were largest in the period before canopy closure, and decreased sharply between age 6 and 11 due to the release of nutrients (particularly K) from the undergrowth, the biomass of which decreased to about 3 t ha^{-1}. The grassland vegetation contained about 35 kg ha^{-1} of N, 3 kg ha^{-1} of P, 95 kg ha^{-1} of K, 16 kg ha^{-1} of Ca, 29 kg ha^{-1} of Mg and 2 kg ha^{-1} of Mn. Corresponding pre-cyclone amounts in the biomass of mature pine forest (Koromani) were 235, 23, 133, 165, 53 and 14 kg ha^{-1}, respectively. Cyclone Sina had a large impact on forest biomass and nutrient content, causing reductions of 30% in biomass and nutrient content at Tulasewa, and of 10% at Koromani, as measured at the end of the study in September 1991 compared to the initial values determined in January 1990. There were no indications that any of the study forests to suffered from nutrient deficiencies.

Amounts of litterfall (mainly needles) generally increased with forest age, but were also dependent on soil characteristics and stocking. Pre-cyclone pine litterfall amounts ranged from about 5 t ha^{-1} in the Tulasewa and Koromani plots to 9 t ha^{-1} in the Korokula forest plot. The associated nutrient returns to the forest floor formed a considerable proportion of the net annual uptake of the pines, particularly of Ca, Mg, Mn and B. Most of K, however, was returned to the forest floor in throughfall and stemflow. Litterfall deposited by cyclone Sina alone exceeded the pre-cyclone annual total by a factor 2 (Korokula forest) to 4 (Tulasewa forest). However, because of the higher nutrient concentrations in fresh material, the associated returns of N, P and K were 3 – 4 times (Korokula) and even 4 (N) to 10–11 (K, P) times (Tulasewa) higher than corresponding annual pre-cyclone returns. Post-cyclone litterfall was low at all sites.

Litter decomposition was fairly rapid, with a 70% decrease in needle litter mass over an 18–20 month period, as measured in a litter bag experiment. Pre-cyclone litter turnover rates (K_L) ranged from 0.4 in Korokula forest to 0.6 in Koromani forest. Decomposition of woody material, however, was much slower as indicated by the presence of severely decomposed wood from a forest stand which had been destroyed seven years earlier in the Tulasewa forest plot. Rates of nutrient release fromn decomposing litter varied between nutrients. More than 60% of the K present in fresh needle litter was released within the first three months after incubation, but the release of N, Ca, and to a lesser extent P and Mg, was much slower, with less than 50% released 1.5 year after incubation in the Koromani forest plot. Due to the differences between the stands it was not possible to detect if decomposition rates changed with age, although the lowest rates were found for litter in the mature forest.

Pre-cyclone measurements of litter standing crop in the forest chronosequence suggested that a slight accumulation of litter (from 10.5 to 13.5 t ha^{-1}) occurred with age. This coincided with a change in the litter layer composition from mainly grass litter in the Tulasewa forest plot to mainly needle litter at the older sites. The large amount of fresh litter deposited by cyclone Sina more than doubled the litter layer mass and nutrient content at all sites. Because such cyclones are a regular phenomenon in Fiji, the litter layer mass and nutrient content will fluctuate considerably during a rotation period.

Under normal weather conditions, the atmospheric nutrient inputs in Fiji are in the lower range of those measured for tropical forests elsewhere (Bruijnzeel, 1989a, 1991). However, during the passage of a cyclone, maritime elements (particularly Na, Cl, Mg and SO_4) may be deposited in quantities far exceeding the normal annual inputs, at least in the coastal areas. Losses of nutrients in water draining from the sites were low, with the exception of elements released by weathering (Na, Mg, Ca, Si, SO_4). Combining these losses with the atmospheric nutrient inputs indicated apparent accumulations of N, P, K and Mn at all sites under investigation, and near neutral budgets or net losses for Ca and Mg. The deposition of seaspray and large quantities of fresh litter during cyclone Sina resulted in increased concentrations of ocean-derived elements in the soil moisture and this, in combination with higher percolation rates due to reduced evapotranspiration, resulted in nutrient losses during the post-cyclone period which were several times higher than pre-cyclone losses.

The atmospheric nutrient input was insufficient to meet uptake by the actively growing forests, the accumulation of nutrients in the litter layer and losses by drainage. Therefore, most of the nutrients taken up by the biomass were supplied by the soil, either by weathering of primary minerals or by depletion of soil reserves. Rates of nutrient uptake from the soil were highest in the period before canopy closure but dropped to a minimum shortly after canopy closure (between age 6 and 11) when substantial amounts of nutrients (particularly K) were transferred from the undergrowth biomass to the soil. Nutrient use efficiency indices (*i.e.* ratio of litterfall mass to the return of nutrients to the forest floor, Vitousek, 1984) indicated that the forests were very efficient in their use of N and P, but less efficient in their use of Ca, Mg and K. The nutrient use efficiency of P, K and Mg decreased considerably after the cyclone event, which was attributed to a less efficient retranslocation of nutrients before abscission of relatively young needles.

The foregoing shows that effects of cyclones on the intra-system nutrient cycle are large and may well last several years during which nutrient requirements of the regenerating forest can be met entirely by release through decomposition of cyclone debris. The fact that the number of cyclones during a rotation and the amount of damage they afflict are unpredictable complicates the evaluation of forest nutrient budgets considerably. Soils in SW Viti Levu are relatively shallow and pine roots were observed to penetrate the zone of active weathering in most instances. This suggests that weathering may provide a significant portion of the nutrients required for biomass production, with the possible exception of P as this element becomes rapidly immobilized in the soil (Clayton, 1979).

Effects of Harvesting and Burning

The Oleolega forest was harvested between December 1990 and July 1991 as a salvage operation after the forest suffered severe damage by cyclone Sina. About 55 t ha^{-1} of merchantable timber were extracted from the catchment and the associated nutrient losses amounted to 45 (N), 5 (P), 29 (K), 23 (Ca), 11 (Mg), 0.6 (Zn), 3.1 (Mn) and 0.1 kg ha^{-1} (B). Cyclone Sina increased the litter layer mass from about 14 t ha^{-1} to 29 t ha^{-1} and a further increase to 37 t ha^{-1} occurred during harvesting. Nutrient concentrations in streamflow from the forested Oleolega catchment were low. The deposition of sea spray and fresh litter during cyclone Sina temporarily increased the EC and pH, as well as the concentrations of most nutrients in streamflow, with the exception of NO_3, NH_4, PO_4 and total P, which showed no significant changes, and those of SO_4 and Mn, which decreased after the event. Concentrations in baseflow tended to return slowly to their pre-cyclone levels during the harvesting operation which lasted until August 1991, although those of NO_3 increased (albeit not significantly). Changes in the chemical composition of streamflow and soil moisture after cyclone Sina were such that any effects of the subsequent harvesting were largely masked. No large changes occurred in the amounts exported from the catchment as a result of cyclone effects and timber extraction. However, although the exports remained low in an absolute sense, exports of K, NO_3 total N, PO_4 and total P were 1.5 (PO_4) to 2.2 (K) times higher than their pre-cyclone values.

Burning of the slash in August 1991 reduced the litter layer mass from 37 to 6 t ha^{-1} and its nutrient content by 245 (N), 10 (P), 72 (K), 95 (Ca), 37 (Mg), 0.8 (Zn), 19.1 (Mn) and 0.3 kg ha^{-1} (B). Comparison of the nutrient contents of soil samples collected before harvesting and after burning showed that most of the nutrients released from decomposing slash and by the burn were retained by the soil. Concentrations of most nutrients in baseflow after the burn only changed significantly when the soil had been thoroughly wetted at the start of the wet season in December 1991. At that time, significant increases were observed in the EC and concentrations of Na, Mg, Ca, NH_4, Cl, HCO_3, NO_3, PO_4, Mn, total N and total P. However, relatively high concentrations of K and SO_4 were already observed in streamflow during the first storm after the burn, but not during subsequent storms, suggesting that these nutrients were rapidly leached from the ash layer. Concentrations of SO_4 in baseflow after the burn were lower than those before the burn, possibly due to increased biological activity in the streamwater (algae). Post-burn exports of Na, Ca, Mg, NH_4, SO_4, Si, Mn and Fe were higher than those obtained from model simulations for the forested situation but the increases could be attributed almost completely to the higher water yield after harvesting and burning. Exports of total P, PO_4, NO_3, K, on the other hand, were higher than would be expected from the increase in water yield alone. However, the absolute nutrient exports in streamflow as a result of harvesting and burning were low in view of the large amounts released from the slash and subsequently retained by the soil. The largest losses were associated with the removal of merchantable timber from the site.

Sustainability of the Pine Plantation Forestry in Fiji

Full rotation (January 1975 – April 1992) nutrient budgets were compiled for the Oleolega forest for various harvesting intensities and two weathering scenarios. Atmospheric inputs were obtained by combining the concentration data collected during the present study with daily rainfall amounts measured at Nadi Airport (1975–1979), Nabou station (1980–1989) and at the Oleolega catchment (1990–1992). Corresponding nutrient exports in streamflow were obtained by combining nutrient concentrations in streamflow before harvesting with simulated streamflow amounts using daily time steps. Weathering inputs could not be evaluated from the soil chemical data collected in the 'false time series' due to differences in soils between the respective sites. Therefore 'pessimistic' (no weathering inputs) and 'optimistic' (all nutrients required for forest growth supplied by weathering) scenarios were computed. Combining the forest's nutrient requirements over the rotation period with estimates of nutrient reserves in the soil (weathering inputs assumed negligible) suggested that nutrient deficiencies were unlikely to occur within the next 5 (Ca) to 19 (K) rotations, provided that harvesting would remain limited to merchantable timber only, and that erosion and associated losses of nutrients with sediment in the streamflow would be minimized. Whole tree harvesting would reduce the number of possible rotations to 2 or 3, before N or P deficiencies could become apparent. Since weathering may provide substantial amounts of nutrients to the ecosystem and because our estimates of N inputs must be underestimates, it may be concluded that plantation forestry with the current management practices is sustainable from a nutrient point of view. Therefore, cyclone damage must at present be considered to be the main factor limiting the biomass production in SW Viti Levu. However, to maintain the current rates of productivity, care should be taken to avoid severe physical deterioration of the shallow soils as a result of soil disturbance during harvesting and subsequent erosion.

Chapter 20

Samenvatting van het Proefschrift 'Water en Nutriënten Dynamiek van *Pinus caribaea* Plantages op Voormalige Graslanden in zuidwest Viti Levu, Fiji'

Het verdwijnen van de natuurlijke bosvegetatie, waarschijnlijk door zwerflandbouw, bosbranden en een te intensieve begrazing in de vorige eeuw heeft geleid tot het ontstaan van een vuur-resistente grasland begroeiing in west Viti Levu, Fiji (Twyford en Wright, 1965), waar de neerslag een sterke seizoenale verdeling vertoont met een jaartotaal van ongeveer 1800 mm. Om te voldoen aan de toenemende vraag op de wereldmarkt naar houtpulp voor papierproduktie, aan de lokale vraag naar hout voor constructiewerkzaamheden, en om werkgelegenheid te scheppen voor de landeigenaren, zijn sinds 1960 door de Fiji Pine Commission *Pinus caribaea* plantages aangeplant op deze *Pennisetum polystachyon* graslanden. Echter, binnen zes jaar na de aanplant van dennen op graslanden in het noorden van Viti Levu, werden sterk verlaagde debieten geobserveerd in stroomgebieden gebruikt voor de waterwinning (Kammer en Raj, 1979). Dit had ondermeer tot gevolg dat tekorten voor de stedelijke watervoorziening ontstonden tijdens droge perioden. Het kappen van deze bossen in de jaren tachtig veroorzaakte nieuwe problemen voor de waterwinning, met name in de vorm van een vermindering in de kwaliteit van het rivierwater door de hoge sedimentconcentraties tijdens regenbuien (erosie). In de jaren tachtig na het kappen van de eerste bosrotatie gevolgd door het branden van de strooisellaag nutriëntentekorten geconstateerd (ontwikkeling van scheuten zonder naalden) in de tweede rotatie. Dit riep vragen op over de duurzaamheid van de huidige wijze van houtproduktie in Fiji (dat wil zeggen, zonder toevoeging van kunstmest). Om meer inzicht te krijgen in deze problemen is

Table 20.1: *Eigenschappen van de vegetatie op de verschillende onderzoekslokaties. Biomassa en bijbehorende produktie gegevens (CAIs) verzameld in de periode voor november 1990 (cycloon Sina).*

Lokatie	**Leeftijd** [jr]	**Dichtheid** [ha-1]	**Dbhob** [m]	**h** [m]	**BO** [m2 ha-1]	**Groene biomassa** [t ha-1]	**CAI(1990)** [t ha-1 jr-1]
Nabou grasland	0	nvt	nvt	nvt	nvt	8	nvt
Tulasewa bos	6	825	0.16	11.6	18.1	70	22.5
Korokula bos	11	822	0.20	14.7	27.5	111	7.6
Koromani bos	15	621	0.25	17.5	31.6	148	9.6
Oleolega bos	15	459	0.25	18.3	15.8	109*	-

Dbhob: Diameter op 1.35 m; h: Boomhoogte; BO: Basale oppervlakte; CAI: Groei in 1990
nvt: Niet van toepassing; *: Biomassa van loofbos niet meegerekend

in 1989 een studie begonnen in een samenwerking van de Vrije Universiteit van Amsterdam en de Fiji Pine Commission (tegenwoordig Fiji Pine Ltd.) met financiering door de stichting voor wetenschappelijk onderzoek van de tropen (WOTRO, projectnr. W84-295). De studie had de volgende doelstellingen:

- Kwantifikatie van eventuele veranderingen in de hydrologische kringloop ten gevolge van herbebossing van *Pennisetum polystachyon* graslanden in zuidwest Viti Levu met *Pinus caribaea*
- Bestudering van de nutriënten kringlopen in graslanden en plantagebossen ter evaluatie van de duurzaamheid van de huidige manier van houtproduktie
- Bestudering van de effekten van kappen gevolgd door het afbranden van de strooisellaag zowel op de hoeveelheid en kwaliteit van rivierwater, als op de fysische en chemische eigenschappen van de bodem

Omdat het niet mogelijk was om een enkele plantage te bestuderen vanaf het planten tot aan de kap van het volwassen bos na 16–20 jaar, werd een serie bossen van verschillende ouderdom geselecteerd om de kringlopen van water- en nutriënten te bestuderen tijdens verschillende fasen in de ontwikkeling van de plantage (Hase en Fölster, 1982; Bruijnzeel, 1983a; Gholz *et al.*, 1985). Hydrologisch, hydrochemisch, micro-meteorologisch en ecologisch onderzoek werd verricht in een grasland bij Nabou, in de zes jaar oude Tulasewa plantage, in de elf jaar oude Korokula plantage en in de vijftien jaar oude Koromani plantage gedurende de periode november 1989 tot oktober 1991, en in het Oleolega stroomgebied tussen 4 januari 1990 en 5 april 1991. Het Oleolega stroomgebied was in 1975 aangeplant met *Pinus caribaea* en werd in 1991 gekapt en verbrand nadat het bos grote schade had ondervonden van cycloon Sina in november 1990. Deze cycloon bleek een grote invloed te hebben op de hydrologie en op de nutriëntenkringlopen van alle bestudeerde bossen. De onderzoekslokaties lagen allemaal in het Nabou plantage gebied (herbebossing vanaf 1975) in zuidwest Viti Levu (Figuur 2.2). De resultaten, verkregen voor de verschillende onderzoekslokaties, zullen hierna in het kort besproken worden. Relevante informatie over de eigenschappen van de vegetatie op de verschillende lokaties ten tijde van de studie is gegeven in Tabel 20.1

De *Pennisetum polystachyon* graslandvegetatie heeft een sterk seizoenaal karakter met een hoge produktie in het natte seizoen (november – april) waarna het bovengrondse deel van het gras grotendeels afsterft tijdens het droge seizoen. Omdat watertekorten ten gevolge van herbebossing van dit soort graslanden juist tijdens droge perioden voorkomen, werden metingen in het grasland voornamelijk tijdens het droge seizoen van 1991 verricht. In tegenstelling tot de graslandvegetatie is de groei van de dennebossen slechts in zeer geringe mate seizoensgebonden en deze bossen vertonen gewoonlijk een hoge biomassaproduktie vanaf het planten tot aan het eind van de rotatie na 16–20 jaar.

Fysische en Chemische Eigenschappen van de Bodems

De bestudeerde bodems onder gras en dennenbos verschilden aanmerkelijk in hun fysische en chemische eigenschappen, wat voornamelijk te wijten was aan verschillen in het onderliggende gesteente (daciet, andesiet en basalt–diabaas) en verschillen in de mate van verwering en erosie. Op basis van de verzamelde gegevens konden de bodems geklassificeerd worden als Mollisols (Nabou grasland, Tulasewa en Korokula plantagebossen) en Oxisols (Koromani plantage), met een redelijke (Koromani) tot goede vruchtbaarheid (Tulasewa). De bodemeigenschappen vertoonden een grote ruimtelijke verscheidenheid in het Oleolega stroomgebied, maar op basis van textuur, diepte en kleur konden twee groepen worden onderscheiden, die gerelateerd waren aan verschillen in het onderliggende gesteente (daciet–trachiet of basalt–diabaas). De bodem in de Korokula plantage was dun (verweerd moedergesteente op 30–80 cm diepte) en bevatte grote hoeveelheden sterk verweerde gesteentemineralen wat erop duidde dat de bodem relatief jong was. De bodem van de Tulasewa plantage was wat verder verweerd en wat dieper (moedergesteente op 80–150 cm diepte), terwijl die van de Koromani plantage het meest verweerd was en weinig gesteentemineralen bevatte. De bodems in het Oleolega stroomgebied vertoonden een grote ruimtelijke variatie. De bodems op de ruggen in het noorden van het stroomgebied (op dacietgesteente) waren vergelijkbaar met die beschreven voor het plantagebos bij Korokula, terwijl die op de hellingen in het zuiden (op basalt–diabaas gesteente) vergelijkbaar waren met de bodems onder de bossen bij Tulasewa en Koromani.

De bestudeerde bodems waren goed gedraineerd, met relatief hoge verzadigde doorlatendheden in de toplaag, en lage tot zeer lage waarden dieper in de bodem. De bulkdichtheden varieerden van 0.97 tot 1.16 g cm^{-3} in de toplaag, en namen toe met de diepte tot 1.1–1.5 g cm^{-3}. Alle bodems hadden hoge porositeiten, zowel in de toplaag (46–51%), als dieper in de bodem (39–64%). De verschillen in fysische eigenschappen, met name in de bulkdichtheden en verzadigde doorlatendheden, tussen de bosbodems onderling waren even groot waren als die tussen de bodems onder gras en bos. Dit wees erop dat er geen grote veranderingen waren opgetreden ten gevolge van herbebossing. Er waren wel aanwijzingen dat de hogere wortelactiviteit van de dennen een verandering in de structuur van de bodem onder de worteldiepte van gras ($\pm$80 cm) tot gevolg had. Dit in tegenstelling tot de bevindingen van Latham (1983) en Bayliss-Smith (1983), die wel verbeteringen in de fysische eigenschappen van de toplaag van de bodem vonden na herbebossing van graslanden met *Pinus caribaea* op het eiland Lakemba in Fiji. De grote ruimtelijke variatie in de eigenschappen van bodems in zuidwest Viti Levu maakt het echter moeilijk om veranderingen ten gevolge van herbebossing te evalueren door een vergelijking van gras en bosbodems.

De beschikbare hoeveelheid water voor planten (59–123 mm) in de dunne bodem (30–80 cm) van de Korokula plantage was niet voldoende om transpiratie door de dennen in stand te houden gedurende een droge periode in mei en juni 1990, zoals bleek uit een verhoogde strooiselproduktie in deze periode. Zulke watertekorten ontstonden niet op de andere lokaties, waar de bossen aangeplant waren op dikkere bodems met inherent grotere hoeveelheden beschikbaar water (>150 mm) voor transpiratie. Dit onderstreept het belang van de bodemdikte als een bepalende factor (naast de neerslaghoeveelheid) of een bos al dan niet onderhevig zal zijn aan periodieke watertekorten. Periodieke watertekorten kunnen verwacht worden in bossen aangeplant op bodems dunner dan 50 cm en het mag gevoeglijk aangenomen worden, dat de produktiviteit van deze bossen in zuidwest Viti Levu laag zal zijn ongeacht de vruchtbaarheid van de bodem.

De fysische eigenschappen van de bodem in het Oleolega stroomgebied veranderden signifikant na het kappen van het bos en het branden van het stooisel. De gemiddelde bulkdichtheid van de toplaag van de bodem steeg van 1.07 g cm^{-3} onder ongestoord bos naar 1.13–1.17 g cm^{-3} na kappen en branden. Deze stijging was echter niet zo groot dat de waarden na kap hoger waren dan die gemeten in de andere ongestoorde plantagebossen (0.97–1.16 g cm^{-3}). De stijging in de bulkdichtheid na kappen en branden viel samen met een sterke daling in de verzadigde doorlatendheid, vooral op nieuw aangelegde wegen, uitsleepsporen en houtverzamelplaatsen. De fysische veranderingen in bodems in gebieden, die niet machinaal verstoord waren, waren niet zodanig dat regenwater afgevoerd werd over het oppervlak (overland flow) tijdens grotere regenbuien, of dat deze veranderingen gevolgen zouden kunnen hebben voor de produktiviteit van de tweede rotatie. Oppervlakkige afvoer van water (en de daarmee geassocieerde erosie) werd echter wel waargenomen op de machinaal verstoorde en sterk gecompakteerde oppervlakken van houtoverslagplaatsen, wegen en uitsleeppaden. Het verdwijnen van de toplaag van de bodem in deze sterk verstoorde gebieden verminderde de bodemdiepte in vele gevallen zo, dat de C-horizont of het verweerde moedergesteente aan het oppervlak kwam. Op deze sterk verstoorde bodems kan derhalve een lage productiviteit van tweede-rotatie plantagebossen verwacht worden om de volgende redenen:

- De bodemdikte, en derhalve ook de beschikbare hoeveelheid water voor transpiratie door planten, was sterk verminderd. Bomen geplant op deze bodems zullen daardoor regelmatig watergebrek ondervinden tijdens droge perioden wat, de groei sterkkan beïnvloeden
- De massieve structuur van de bodem kan een remmende invloed hebben op de ontwikkeling van het wortelstelsel van de aangeplante bomen, en daarmee ook op de bovengrondse biomassa produktie (Van der Weert, 1974)

De vruchtbaarheid van de bodems in de onderzoeksgebieden was redelijk (Koromani plantage) tot goed met de grootste hoeveelheid beschikbare nutriënten in de relatief jonge bodem onder de Korokula plantage. De Bray-II (Bray en Kurtz, 1945) en de Ca-lactaat extractiemethoden voor de bepaling van voor planten beschikbaar fosfor gaven sterk verschillende resultaten. De resultaten van de laatstgenoemde methode (3.5–5.0 kg ha^{-1}) waren onwaarschijnlijk laag mede gelet op de hoeveelheden fosfor die reeds opgenomen waren in de bovengrondse biomassa en in de strooisellaag. De resultaten verkregen met de Bray-II methode waren realistischer (24–164 kg ha^{-1}).

Watergebruik van Graslandvegetatie en Dennebossen

Schattingen voor de evapotranspiratie (ET) door grasland in geselecteerde droge perioden (n= 59 dagen) tijdens het droge seizoen van 1991 werden verkregen door het bepalen van de vochtverliezen in de bodem met behulp van een Didcot capacitievebodemvochtsonde. Deze ET_{sm}-fluxen en gelijkertijd boven het gras verzamelde micrometeorologische gegevens, werden gebruikt om de oppervlakte weerstand (surface resistance, r_s) te berekenen met behulp van de geïnverteerde Penman-Monteith vergelijking. Op zijn beurt werd r_s gerelateerd aan veranderingingen in de bladoppervlakte-index (LAI) van gras en de gevonden regressievergelijking werd vervolgens gebruikt om een gemiddelde dagelijkse verdamping van 1.0($\pm$0.3) mm dag^{-1} uit te rekenen voor een 131 dagen lange periode, gedurende welke het meeste gras dood was. De Penman-open-water verdamping (E_0) voor dezelfde periode was gemiddeld 3.7 mm dag^{-1} wat resulteerde in een erg laag quotiënt van 0.26 voor ET/E_0. Dezelfde aanpak voor de bepaling van r_s kon niet toegepast worden in de bestudeerde bossen aangezien te lage waarden voor ET_{sm} werden verkregen omdat het niet mogelijk was om bodemvochtsmetingen te maken tot op een diepte onder die van de dennewortels.

Halfuurlijkse waarden voor de ET van de Tulasewa en Koromani plantagebossen werden daarom bepaald door een combinatie van verschillende micro-meteorologische methoden te gebruiken, met name de Bowen ratio en temperatuurfluctuatie – energiebalans methoden en de Penman-Monteith methode. Tevens werd de stroomgebied–waterbalans methode gebruikt om schattingen te verkrijgen van de verdamping tijdens het natte zowel als het droge seizoen voor het Oleolega stroomgebied. Zoals eerder vermeld, passeerde cycloon Sina Fiji in November 1990. Dit had als gevolg dat de bladmassa van alle bossen aanzienlijk verminderde door ontbladering, zowel als de totale bovengrondse biomassa van het bos bij Tulasewa waar de bosdichtheid van 835 bomen ha^{-1} naar 489 bomen ha^{-1} daalde. Het zal duidelijk zijn dat dit het watergebruik van het bos beïnvloedde.

De voor het droge seizoen van 1990 (dat wil zeggen in de periode voor cycloon Sina) berekende ET waarden varieerden van 3.3 mm dag^{-1} voor het vijftien jaar oude bos in het Oleolega stroomgebied tot 4.0 mm dag^{-1} voor het zes jaar oude Tulasewa bos. De bijbehorende Penman-open-water verdampingen waren respectievelijk 3.8 en 3.5 mm dag^{-1}, zodat waarden van 0.9 en 1.1 werden verkregen voor de quotiënten van ET/E_0. Hoewel E_0 gemiddeld hoger was tijdens het droge seizoen van 1991 (4.2 mm dag^{-1}), werd er toch een relatief lage ET-waarde van 3.0 mm dag^{-1} berekend voor de Koromani plantage. Dit was zeer waarschijnlijk te wijten aan een verminderde transpiratie ten gevolge van de ontbladering teweeggebracht door cycloon Sina in november 1990. Een relatief lage waarde van 0.7 werd berekend voor het quotiënt van ET/E_0 tijdens het droge seizoen in 1991. De lagere transpiratie van het bos bij Tulasewa, waar 40% van de bomen waren omgewaaid, resulteerde in aanmerkelijk hogere vochtgehalten in de bodem tijdens het droge seizoen van 1991, vergeleken met die gemeten in dezelfde periode in 1990.

Kortgolvige stralingsmetingen gemaakt boven de twee vegetatietypen toonden aan dat de reflectiecoëfficient daalde van 0.18 voor gras naar 0.10–0.13 voor de dennebossen, wat resulteerde in hogere netto stralingswaarden voor de bossen. De bodemwarmteflux was reeds laag onder de dichte grasvegetatie bij het Oleolega stroomgebied, maar nog lagere waarden werden gemeten in de dennebossen. De opslag van energie binnen het bos was laag. Uit deze waarnemingen bleek dat de hoeveelheid beschikbare energie voor verdeling over de voelbare en latente warmtefluxen hoger was boven bos dan boven gras. Herbebossing had tevens tot gevolg dat de aerodynamische weerstand daalde van 31 s m^{-1} voor het gras naar ongeveer 14 s m^{-1} voor de bossen. De veranderingen in deze factoren geven aan dat de verdamping door de bosvegetatie tijdens het natte seizoen hoger zal zijn dan die van het gras. Herbebossing van de graslanden verkleinde de dagelijkse gang van de temperatuur en luchtvochtigheid.

Verliezen van water door interceptie van neerslag in het kronendak en in de strooisellaag in de plantagebossen van verschillende ouderdom werden bepaald door het meten van de hoeveelheden water die het respectievelijk het kronendak (neerslag), de bosvloer (doorval en stamafvoer), en de bodem (strooiselpercolaat) bereikten tijdens regenbuien. De relatieve interceptieverliezen waren ongeveer even groot in de verschillende plantagebossen en varieerden tussen 26% van de neerslag in de vijftien jaar oude Koromani plantage en 29% van die in de elf jaar oude Korokula plantage. In alle plantages bedroegen de interceptieverliezen in de strooisellaag rond de 10% van de neerslag. De gemodelleerde interceptieverliezen in de vegetatie en strooisellaag (Analytisch model van Gash en strooisellaag interceptiemodel ontwikkeld in deze studie, Paragraaf 5.5) van het Nabou grasland bedroegen om en nabij de 10% van de neerslag. Het interceptieverlies in het zes jaar oude Tulasewa bos bedroeg 27%. Dit wijst erop dat een stijging in de totale interceptieverliezen in het kronendak en in de strooisellaag verwacht kunnen worden van rond de 15% van de neerslag in de periode tussen aanplant van het bos en de bijna afgeronde ontwikkeling van het kronendak ongeveer zes jaar later. De ontbladering ten gevolge van cycloon Sina had als resultaat, dat de verliezen door interceptie tijdelijk (mogelijk gedurende 1 à 2 jaar) enige procenten kleiner werden in de bossen waarin het aantal bomen niet drastisch afgenomen was. Een permanente daling van de interceptieverliezen mag verwacht worden in de Tulasewa plantage, door de daling van de bosdichtheid met 40%.

Een vergelijking van de verliezen van water door verdamping gevonden voor *Pennisetum polystachyon* grasland en *Pinus caribaea* plantages toonde aan dat de verliezen met 300 tot 400 mm stegen binnen zes jaar na de aanplant van de plantagebossen, en dat de verdampings verliezen daarna min of meer constant bleven. Dit zal ongetwijfeld leiden tot reducties van vergelijkbare grootte in de oppervlaktewaterhoeveelheden na herbebossing van deze graslanden. Het verschil in waterverbruik was voornamelijk te wijten aan verschillen in de verliezen door transpiratie tussen het dode gras en de actief groeiende dennen. Verschillen in neerslaginterceptie karakteristieken van de twee vegetatietypen zijn minder belangrijk in het droge seizoen, maar kunnen een wel grote rol spelen in het waterverbruik tijdens het natte seizoen.

Hydrologische metingen in het Oleolega stroomgebied wezen uit dat het waterverbruik met 7–14% daalde gedurende een vrij droge periode na het kappen van het volwassen bos en het verbranden van de strooisellaag ten opzichte van de beboste situatie. Toch was deze geringe reductie genoeg om een stijging van 51% in de waterafvoer te bewerkstelligen ten opzichte van de gemodelleerde afvoer voor het beboste stroomgebied voor dezelfde periode. (Hoofdstuk 15). Zowel de minimum afvoeren, die 20–80% hoger waren dan de gemeten minimum afvoeren in de beboste situatie, en de piekafvoeren waren aanmerkelijk hoger na het kappen van het bos en het verbranden van de strooisellaag. Omdat de periode na kappen en branden aanmerkelijk droger was dan gewoonlijk (totale neerslag was 887 mm i.p.v. 1418 mm) kunnen grotere reducties in de verdamping, en grotere stijgingen in de debieten verwacht worden in jaren met neerslaghoeveelheden dichter bij het lange termijn gemiddelde.

Concluderend kunnen we stellen, dat de huidige studie aantoont, dat het aanplanten van *Pinus caribaea* plantages op seizoenale graslanden in zuidwest Viti Levu zal leiden tot een vermindering in de waterafvoer, en daardoor tot watertekorten, tijdens het droge seizoen door verhoging van de verliezen door transpiratie, en waarschijnlijk ook tijdens het natte seizoen door de verschillen in interceptie tussen de vegetatie typen. Op zijn beurt zal het kappen van het bos aan het eind van de rotatie gevolgd door het verbranden van de strooisellaag leiden to verhoogde afvoeren. Omdat de graslandvegetatie binnen een paar maanden na het branden teruggekeerd was en de verstoring van de bodem ten gevolge van de kap niet leidde tot oppervlakkige afvoer van regenwater op grote schaal, kan verwacht worden dat het watergebruik na het kappen/branden ongeveer gelijk zal zijn aan dat van voor de herbebossing.

Nutriënten Kringloop

De produktiviteit van de bestudeerde plantagebossen was hoog in de periode voor de destruktie en ontbladering van de bossen door cycloon Sina, zoals blijkt uit de hoge CAI waarden gegeven in Tabel 20.1. De totale bovengrondse biomassa van bos en ondergroei steeg van 8 t ha^{-1} in Nabou grasland tot 150 t ha^{-1} in het vijftien jaar oude Koromani bos. De opname van nutriënten uit de bodem voor de produktie van biomassa was het hoogst tijdens de snelle ontwikkeling van het nutriëntenrijke kronendak, ongeveer zes jaar na het aanplanten, en daalde scherp nadat het kronendak zich sloot, mede door het vrijkomen van nutriënten (vooral kalium) vanuit de ondergroei, waarvan de bovengrondse biomassa daalde tot ongeveer 3 t ha^{-1}. De vegetatie in het Nabou grasland bevatte ongeveer 35 kg ha^{-1} stikstof, 3 kg ha^{-1} fosfor, 95 kg ha^{-1} kalium, 16 kg ha^{-1} calcium, 29 kg ha^{-1} magnesium en 2 kg ha^{-1} mangaan. Bijbehorende waarden voor het vijftien jaar oude Koromani bos, bepaald in de periode voordat cycloon Sina schade aan het bos toebracht, waren respectievelijk 235, 23, 133, 165, 53, en 14 kg ha^{-1}. Geen van de bestudeerde bossen toonde tekenen van nutriëntentekorten. Ten gevolge van de toegebrachte schade door cycloon Sina waren de bovengrondse biomassa en nutrientenopslag in de bomen in september 1991 30% lager in de Tulasewa plantage en 10% lager in de Koromani plantage ten opzichte van die in januari 1990. De cycloon had derhalve een grote invloed op de biomassa en de nutriëntenoplag in de bossen.

De strooiselproduktie door de dennen (voornamelijk naalden) vertoonde een stijging met de ouderdom van het bos, maar was ook afhankelijk van de dichtheid van het bos en van bodemeigenschappen (met name beschikbare hoeveelheid water). De jaarlijkse strooiselproduktie in de periode voor cycloon Sina varieerde tussen 5 t ha^{-1} in de Tulasewa en Koromani plantages en 9 t ha^{-1} in de Korokula plantage. De nutriëntentoevoer naar de bodem in strooisel vormde een aanzienlijk deel van de netto jaarlijkse opname door de bossen, met name voor Ca, Mg, Mn en B. Echter, het grootste gedeelte van kalium keerde terug naar de bosvloer in doorval en stamafvoer, en niet in het strooisel. De stooiselproduktie tijdens de passage van cycloon Sina was meer dan twee (Korokula) tot vier (Tulasewa) keer de normale jaarlijkse produktie (d.w.z. in jaren zonder cyclonen). De nutriëntenconcentraties in het relatief verse strooisel, gedeponeerd tijdens de cycloon, waren hoger dan die in de normale strooiselval. Dit resulteerde in 3–4 keer hogere deposities van N, P en K (Korokula) en 4 (N) tot 10–11 (P, K) keer hogere deposities (Tulasewa) in strooisel gedeponeerd tijdens de cycloon, dan in die gedeponeerd tidens de gehele voorafgaande periode. De strooiselproduktie bleef laag na de ontbladering van de bossen door cycloon Sina.

De afbraak van het strooisel op de bosvloer was relatief snel, met gemeten gewichtsverliezen voor naalden (in stooiselzakjes) van ongeveer 70% over een periode van 18–20 maanden. Omzettingssnelheden, berekend als het quotiënt van de jaarlijkse naaldval en de hoeveelheid naalden op de bosgrond (K_L, in $jaar^{-1}$), in de periode voor de ontbladering door cycloon Sina varieerden tussen 0.4 (Korokula) en 0.6 $jaar^{-1}$ (Koromani). De afbraak van hout was veel minder snel, aangezien verrot hout van een in 1983 vernielde plantage nog steeds op de bosvloer aanwezig was in het bos bij Tulasewa. De omzettingssnelheden waren verschillend voor de verschillende voedingsstoffen. Meer dan 60% van het oorspronkelijk in de naalden aanwezige kalium was uitgespoeld binnen drie maanden na het plaatsen van de strooiselzakjes op de bosvloer. De omzettingssnelheden voor N en Ca, en in mindere mate voor Mg en P, waren veel lager en minder dan de helft van de oorspronkelijke inhoud van deze elementen was omgezet binnen een jaar na de plaatsing van de strooiselzakjes op de bosvloer in de Koromani plantage. Door de onderlinge verschillen tussen de bossen konden geen trends in de decompositiesnelheden met de bosleeftijd bepaald worden, al leek het erop dat de afbraak het langzaamst was in het oudste bos.

Gegevens over het gewicht van de strooisellaag in de Tulasewa, Korokula en Koromani plantages verzameld in de periode voor ontbladering suggereerde een lichte stijging in de massa van de strooisellaag met de ouderdom van het bos (van 10.5 t ha tot 13.5 t ha^{-1}). Tegelijkertijd veranderde de compositie van de strooisellaag die voornamelijk bestond uit gras resten in de jonge Tulasewa plantage in een strooisellaag voornamelijk bestaande uit dennenaalden in het volwassen Koromani bos. De grote hoeveelheid strooisel gedeponeerd door cycloon Sina ruim verdubbelde de massa en nutriënteninhoud van de strooisellaag in alle bestudeerde plantagebossen. Omdat zulke cyclonen regelmatig voorkomen in de Fiji eilanden zijn grote fluctuaties in de massa en nutriënteninhoud van de strooisellaag mogelijk binnen een rotatieperiode.

Onder normale weersomstandigheden (d.w.z. geen cyclonen) valt de atmosferische nutriënteninvoer in zuidwest Viti Levu in het lagere bereik van die gemeten boven tropische bossen op andere plaatsen (Bruijnzeel, 1989a, 1991). Echter, tijdens cyclonen kunnen oceanische elementen (zoals Na, Cl, Mg, en SO_4) gedeponeerd worden in de kustgebieden (en waarschijnlijk ook verder landinwaarts) in hoeveelheden die veel groter zijn dan de normale jaarlijkse droge en natte depositie. De verliezen van voedingsstoffen in drainage van de onderzoekslokaties waren relatief laag, met uitzondering van die elementen, die vrijkomen bij verwering van het gesteente (Na, Mg, Ca, Si en SO_4). Vergelijking van de atmosferische nutriënteninvoer met de verliezen in drainage suggereerde, dat N, P, K en Mn accumuleerden in de bossen, terwijl neutrale budgetten of kleine verliezen werden geconstateerd voor Ca en Mg. Verhoogde ionenconcentraties werden waargenomen in het bodemvocht in de plantages na de depositie van oceanische elementen en grote hoeveelheden vers strooisel door cycloon Sina en dit, in combinatie met verhoogde drainagesnelheden door verminderde neerslaginterceptie en transpiratie, resulteerde in belangrijk grotere verliezen van nutriënten met percolerend bodemwater in de periode na de cycloon.

De atmosferische nutriëntendepositie was niet voldoende om de opname van voedingsstoffen door de snelgroeiende bossen, de immobilisatie van deze stoffen in de strooisellaag, en de verliezen in percolerend water te compenseren. Dit leidde ertoe, dat de bodem een groot gedeelte van de benodigde voedingstoffen voor de produktie van biomassa moest leveren, zowel vanuit de bodemreserves als door verwering van bodem- en gesteentemineralen. Zoals reeds vermeld was de opname van voedingsstoffen het hoogst tijdens de ontwikkeling van het kronendak ongeveer zes jaar na het planten en werden er in deze periode aanzienlijke hoeveelheden nutriënten aan de bodem onttrokken. Na het sluiten van het bladerdak, echter, kwamen nutriënten (vooral kalium) vrij uit de ondergroei, en de onttrekking vanuit de bodem was daardoor laag in de periode van zes tot elf jaar na planten. De vraag naar nutriënten vanuit de bodem steeg weer wat in ouder plantagebos, maar bleef laag ondanks een relatief hoge produktie omdat een groot deel van de voedingsstoffen opgenomen werd voor de produktie van nutriënten-arm hout. Berekende efficiëntie-indexcijfers voor het gebruik van voedingsstoffen (Vitousek, 1984) door de bossen toonden aan, dat de bossen zeer efficiënt met stikstof en fosfor omgingen, en minder efficiënt met calcium, magnesium en kalium. De efficiëntie-indexcijfers gingen sterk omlaag, nadat de bossen beschadigd waren door cycloon Sina, wat te wijten viel aan de geringe translokatie van voedingsstoffen voor het afstoten van de relatief jonge naalden.

Het voorgaande laat zien, dat de effekten van cycloonschade op de kringloop van voedingsstoffen groot zijn, en dat de hoeveelheden tijdens de cycloon gedeponeerde voedingsstoffen voldoende zijn om voor enkele jaren in de opname van het herstellende bos te voorzien via afbraak van het verse strooisel. Het feit, dat het aantal cyclonen in een rotatieperiode, en de eventuele schade die ze toe brengen aan de plantages, onvoorspelbaar zijn, bemoeilijkt het opstellen van een nutriëntenbudget over een rotatie voor de plantagebossen in Fiji.

De bodems in zuidwest Viti Levu zijn relatief dun, en het wortelstelsel van de dennen reikt over het algemeen tot in de zone waar actieve verwering plaatsvindt, zoals in spleten en scheuren in het verweerde moedergesteente. Dit wijst erop dat verwering een belangrijk aandeel kan leveren van de nutriënten, die nodig zijn voor de groei van de bossen, waarbij fosfor een mogelijke uitzondering vormt omdat dit element snel geïmmobiliseerd wordt in de bodem (Clayton, 1979).

Effekten van Kappen en Branden op de Nutriëntenhuishouding

Het bos in het Oleolega stroomgebied werd gekapt tussen december 1990 en juli 1991 als een soort reddingsoperatie, nadat het bos zwaar beschadigd was door cycloon Sina. Er werden in totaal ongeveer 55 ton ha^{-1} hout weggehaald uit het stroomgebied, en dit leidde tot de uitvoer van 45 kg ha^{-1} stikstof, 5 kg ha^{-1} fosfor, 29 kg ha^{-1} kalium, 23 kg ha^{-1} calcium, 11 kg ha^{-1} magnesium, 0.6 kg ha^{-1} zink, 3.1 kg ha^{-1} mangaan en 0.1 kg ha^{-1} boor. Al voor het kappen begon, was de massa van de strooisellaag flink gestegen van ongeveer 14 naar 29 ton ha^{-1} door de cycloonschade aan het bos, en de strooiselmassa steeg verder tijdens het kappen naar 37 ton ha^{-1}. De concentraties van voedingsstoffen in het rivierwater vanuit het beboste stroomgebied waren laag. Echter, na de depositie van oceanische elementen en vers strooisel door cycloon Sina gingen de EC, pH en de concentraties van de meeste elementen omhoog, met uitzondering van die van nitraat, ammonia, fosfaat en totaal fosfor die niet signifikant veranderden, en die van sulfaat en mangaan, die signifikant lager waren na de gebeurtenis. Tijdens het kappen in het natte seizoen van 1991 leken de ionenconcentraties in de basisafvoer langzaam terug te keren naar de niveaus van voor de cycloon, met uitzondering van die van nitraat, die leken te stijgen (hoewel niet signifikant). Veranderingen in de chemische samenstelling van de stormafvoer na de cycloon en het kappen van het bos waren niet dusdanig, dat dit grote gevolgen had voor de export van nutriënten in het rivierwater, ten opzichte van die vanuit het ongestoorde stroomgebied. Echter, hoewel de geëxporteerde hoeveelheden laag bleven in absolute zin, waren de geëxporteerde hoeveelheden van kalium, nitraat, totaal stikstof, fosfaat en totaal fosfor 1.5 (PO_4) tot 2.2 (K) keer zo hoog als de hoeveelheden geëxporteerd vanuit het ongestoorde stroomgebied.

Het verbranden van de strooisellaag in augustus 1991 reduceerde de strooiselmassa van 37 naar 6 ton ha^{-1} en de nutriënteninhoud met 245 (N), 10 (P), 72 (K), 95 (Ca), 37 (Mg), 0.8 (Zn), 19.1 (Mn) en 0.3 kg ha^{-1} (B). Een vergelijking tussen de beschikbare voedingsstoffen in de bodem voor het kappen en die aanwezig na het branden toonde aan dat de meeste voedingsstoffen die door decompositie en branden vrijgekomen waren, terecht waren gekomen in de bodemreserves. Na het branden veranderden de nutriëntconcentraties in de basisafvoer signifikant, maar niet voordat de bodem voldoende vochtig was geworden aan het begin van het natte seizoen in december 1991. Hierna werden signifikante stijgingen geobserveerd in de EC en de concentraties van Na, Mg, Ca, NH_4, Cl, HCO_3, NO_3, PO_4, Mn, totaal N en totaal P. De concentraties van kalium en sulfaat waren relatief hoog in de afvoer tijdens de eerste regenbui na het branden, maar niet in die van de daaropvolgende regenbuien. Dit wees erop, dat deze elementen snel uitspoelden vanuit de aslaag. De sulfaatconcentraties in de basisafvoer waren lager in de periode na het branden dan in de periode daarvoor, wat mogelijk te wijten is aan biologische activiteit in het rivierwater (algen). De geëxporteerde hoeveelheden Na, Ca, Mg, NH_4, SO_4, Si, Mn en Fe in rivierwater in de periode na het branden waren hoger dan die verkregen via een modelsimulatie voor de beboste situatie over dezelfde periode. De extra uitvoer was bijna geheel te wijten aan de verhoging van de waterafvoer na het kappen/branden. Echter, de geëxporteerde hoeveelheden totaal P, PO_4, NO_3, en K waren hoger dan verwacht zou mogen worden op basis van de verhoogde debieten. De verliezen aan voedingsstoffen in rivierwater na het kappen en branden bleven echter laag vergeleken bij de hoeveelheden, die vrijkwamen vanuit de strooisellaag na het branden. De grootste verliezen tijdens het kappen en branden waren daarom die in het geëxporteerde hout.

Duurzaamheid van de Plantage Bosbouw in Fiji

Nutriëntenbudgetten over een volledige rotatieperiode (januari 1975 – april 1992) werden opgesteld voor het Oleolega stroomgebied, waarbij rekening werd gehouden met verschillende intensiteiten van kap en met twee scenarios voor de nutriëntenbijdragen van verwering. De atmosferische nutriëntendepositie werd berekend door de neerslaggegevens verzameld in het Oleolega stroomgebied (hoeveelheden en concentraties) te combineren met dagelijkse neerslagtotalen verzameld op de luchthaven van Nadi (1975–1979) en bij het Nabou hoofdkwartier (1980–1989). De bijbehorende export van voedingsstoffen in rivierwater uit het stroomgebied over de rotatieperiode werd verkregen door de gemiddelde ionenconcentraties in rivierwater vanuit het beboste stroomgebied te kombineren met gesimuleerde dagelijkse debieten. Door de verschillen in de bodems van de verschillende bossen kon de bijdrage van verwering aan de nutriëntenopname van het bos niet worden bepaald. Daarom werden 'pessimistische' (geen bijdrage van verwering, nutriënt opname volledig uit bodemreserves) en 'optimistische' (geen opname uit bodemreserves, alle voedingsstoffen geleverd door verwering) budgetten opgesteld. Door de voor de groei benodigde hoeveelheden nutriënten te combineren met de beschikbare hoeveelheden voedingsstoffen in de bodem konden schattingen worden gemaakt voor het aantal mogelijke rotaties. Het pessimistische budget suggereerde, dat het onwaarschijnlijk was dat nutriëntentekorten voor zouden komen binnen de volgende vijf (Ca) tot 19 (K) rotaties, onder de voorwaarden dat alleen de stammen (inclusief bast) zouden worden weggehaald en dat erosie, en de daarmee geassocieerde nutriëntverliezen, tot een minimum beperkt zou worden. Het weghalen van de bomen in zijn geheel verminderde het mogelijke aantal rotaties naar 2–3 voordat er tekorten in stikstof en fosfor zouden ontstaan. Omdat de verwering, die in dit budget buiten beschouwing bleef, toch een belangrijk aandeel in de voedingsstoffenvoorziening kan vormen, en omdat de invoer van stikstof onderschat was, is het waarschijnlijk, dat de huidige bosbouw in zuidwest Viti Levu duurzaam is vanuit het oogpunt van de bodemvruchtbaarheid. Daarom moet beschadiging van de plantages door cyclonen beschouwd worden als de belangrijkste bedreiging voor de houtproduktie. Echter, om de huidige snelheid van houtproduktie vast te houden moet al het mogelijke gedaan worden om de fysische achteruitgang van de dunne bodems door verstoring tijdens kappen, en de daarmee geassocieerde erosie, te voorkomen.

Chapter 21

Acknowledgements

The contents of this book reflect the efforts of a large number of people who were involved in the study or who supported me otherwise throughout the data collection period and writing phase.

I am grateful for the financial and material support from the Netherlands Foundation for the Advancement of Tropical Research (WOTRO, grant no. W84-295), from the Faculty of Earth Sciences from the Vrije Universiteit van Amsterdam, as well as from the Fiji Pine Commission (now Fiji Pine Limited).

Hans Vugts spent a lot of time on the paperwork associated with the project, the testing of micro-meteorological equipment and the preparation of the equipment for shipment to Fiji on two occasions. It has been a great pleasure to work with him as he provided a very pleasant and relaxed working environment and always found time to help me out when I was struggling with technical or scientific problems. My wife and the other guests in our home in Nadi greatly appreciated his ability to prepare the best Irish coffee in Fiji.

Sampurno Bruijnzeel wrote the initial proposal for this study in 1988 after a meeting with Peter Drysdale, the former manager of the Fiji Pine Commission during a workshop in Taiwan. When the funding for it finally came through (after being denied repeatedly), his guidance in the field and during the data processing phase, as well as his critical remarks on the draft version of this dissertation greatly improved the final result. I am very grateful for the way he supported me throughout the study period, and I hope that we can continue to work together in the future.

Fred Scatena managed to review this dissertation within a very short time and I am very grateful for his willingness to do so.

In Fiji, my friend and counterpart Mr. Temesi Tora Rawaqa not only taught me a great deal about the practical aspects of plantation forestry, but also introduced me to the Fijian way of life and took care of all the practical problems we encountered in the field. My wife Corjona and I particularly enjoyed the meetings around the *tanoa*, the great food from the *lovo*, and the hospitality shown by him, his wife Salote and their children. Furthermore, by continuing the hydrological measurements in the Oleolega catchment under adverse conditions (and in his spare time) after I had left Fiji, he greatly improved the results obtained for this particular part of the study. *Vinaka Vaka Levu*!

Mr. James Dunn, Dr. Jonathan Heuch, Mr. Gus Carty, Mr. Rajat Kumar, Mr.

Naca Yalimaitoga, Mr. Peni Turagabaleti, Mr. Jona Bale and Mr. Peni Were from the Fiji Pine Commission all contributed substantially to the smooth running of the project, either by supplying valuable information, or by providing transport, personnel or funding whenever necessary. The discussions we had on the various research objectives made it much easier for me to focus on the issues relevant to the Fiji Pine Commission.

The former manager of the Fiji Pine Commission, Mr. Peter Drysdale, is acknowledged for setting-up the initial framework for the cooperation between the Fiji Pine Commission and the Free University of Amsterdam.

The people working at the Nabou station from the Fiji Pine Commission, particularly Mr. Joe Buakula, Mr. K. Laga, and Saimoni are acknowledged for pulling my car out of the mud on several (rainy) occasions, for providing technical assistance to the project, as well as for the maintenance of a pluviograph placed at the Nabou meteorological station for calibration purposes. *Vinaka Vaka Levu.*

Mrs. Karalaini Marriot kindly gave her permission to carry out the grassland study in her 'backyard' and Mr. Fereti Dumaru and Mr. Joseva Maone are acknowledged for their help in the negotiations.

Mr. Ben Mitai and and Rupesh from TROPIK Wood Industries Ltd. are acknowledged for allowing me to make frequent use of the oven and weighing facilities at the plant in Drasa, as well as for keeping me informed on the logging activities in the Oleolega catchment.

During our visits to Suva it was always a pleasure to visit Dr. Mahendra Kumar and his family. I thank him for his hospitality, his interest in the project and for his professional help with the ceptometer measurements.

I am grateful for the technical assistance from the people of the Fiji Meteorological service in Nadi, particularly Mr. Ram Krishna, Mr. Eroni Puamau and Dr. John Refveim, as well as for the long-term climatic data which were provided to the project free of charge.

The assistance of Tevita Sauturaga and Malakai Jr. with porometer measurements, the biomass study, and the sorting of the litter layer material made the collection of data a lot easier. *Vinaka Vaka Levu.*

Without the presence of our neighbours and close friends Malakai, Anaseini Ravesi, and Elenoa Verevanua Tuibuabua, our life in Fiji would not have been as good as it was. Corjona and I like to thank them for everything they did for us and for our guests. We will never forget them and wish them all the best. *Vinaka Vaka Levu*!

The MSc. students Frits Beekman, Arnoud Frumau, Jaap schellekens, Peter Assenberg, Eise Harkema, Harald Opdam and Bart van Well all came to Fiji to assist me with the field measurements. Without their help we could not have managed to accumulate the amount of data on which this dissertation has been based. Their preliminary work and programming skills made data processing a lot easier during the writing phase.

The Cooperative Research Centre for Catchment Hydrology from the CSIRO Division of Water Resources in Canberra, Australia, made heat pulse equipment for measuring sapflow velocities available to the project, and Rob Vertessy is acknowledged for installing the instruments. He also arranged for me to work with the TOPOG model during a two week stay at the laboratory in Canberra. Corjona and I are particularly grateful for the hospitality Rob and Deborah Vertessy showed to us during this period.

More than a thousand water and soil samples were analyzed at the laboratory of the FES-VUA by Tini Bäer, Freek Wals, Hetty Schäfer, Wilma Meijer, John Kist, Bob

Stokvis, Martin Konert, Peter Willekes, Roel van Elsas and Fatima Elkhalouki. I am very grateful for the professionality and patience with which they did the job.

Theo Hamer, Hans Bakker and Nico van Harlingen from the FES-VUA mechanical workshop developed and constructed some of the hydrological and micro-meteorological equipment and were always able to find creative solutions for technical problems. Their skills in erecting meteorological towers within very short periods of time were of great value to the project. Johan de Lange and Ron Lootens from the FES-VUA department of electronics helped me out on several occasions when electronic instuments failed.

Edwin Henneken and Niek Jan Bink are acknowledged for their comments on the micro-meteorological parts of this dissertation.

Ilse and Adam Yared, thank you for taking us out to your beautiful Namotu Island on several occasions. We really enjoyed your company, and being away from the daily routines, as well as having a good swim.

Neyah Wayah Timisela always managed to enrich my rather dull computer-life by coming up with crazy business proposals, I wish you, Dori, and Dave good luck.

My family has not seen a lot of me lately, and I thank them for their support and consideration.

Finally I should thank my wife Corjona for keeping up with a workaholic husband over the past years.

Part VI

Bibliography and Appendices

Bibliography

[1] P.G. Adlard. Quantitative effects of pruning *Pinus patula* in Malawi. *Commonwealth Forestry Review*, 48(4):339–349, 1969.

[2] AID-USDA Soil Management Supports Services. Keys to soil taxonomy. Technical Monograph 6, Agency for International Development, USDA, 1983.

[3] H.M.S. Amir. Nutrient cycling under tropical rain forest of Peninsular Malaysia with a special reference to Tekam Forest Reserve, Pahang, D. M. Paper presented at the FRIM-IHP-UNESCO Regional Seminar on Tropical Forest Hydrology, Kuala Lumpur, Malaysia, Sep 1989.

[4] J.M. Anderson, J. Proctor, and H.W. Vallack. Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak. III. decomposition processes and nutrient losses from leaf litter. *Journal of Ecology*, 71:503–528, 1983.

[5] J.M. Anderson and T. Spencer. Carbon, nutrient and water balances of tropical rain forest ecosytems subject to disturbance: Management implications and research proposals. MAB Digest 7, UNESCO, Paris, 1991.

[6] J.M. Anderson and M.J. Swift. Decomposition in tropical forests. In S.L. Sutton, T.C. Whitmore, and A.C. Chadwick, editors, *Tropical Rain Forest: Ecology and Management*, pages 287–309. Blackwell Scientific Publications, Oxford, 1983.

[7] C. Andrus. Soil erosion and streamflow from tropical grasslands: How much do we really know? Working paper, East-West Center, Honolulu, Hawaii, Jul 1986.

[8] D.E. Angus and P.J. Watts. Evapotranspiration - how good is the Bowen ratio method? *Agricultural Water Management*, 8:133–150, 1984.

[9] R.A. Anthes. Tropical cyclones, their evolution, structure and effects. *Meteorological Monographs*, 19, 1982.

[10] C.A.J. Appelo and D. Postma. *Geochemistry, Groundwater and Pollution*. Balkema, Rotterdam, 1993.

[11] S. Pal Arya. *Introduction to Micrometeorology*, volume 42 of *International Geophysics Series*, chapter 3, pages 21–36. Academic Press Inc., San Diego, California, first edition, 1988.

[12] P. Assenberg. Effects of cyclone disturbance and subsequent log extraction on water yield and quality in the Oleolega catchment. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit Amsterdam, The Netherlands, 1993.

[13] S.R. Baconguis and B.B. Jasmin. Influences of three major forest vegetations on streamflow characteristics. *The Philippine Lumberman*, pages 6–38, 1984.

[14] I.C. Baillie. Soil characteristics and mineral nutrition of tropical wooded ecosystems. In J. Proctor, editor, *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*, pages 15–26. Blackwell Scientific Publications, London, 1989.

[15] C. Bailly, G. Benoit de Coignac, C. Malvos, J. M. Ningre, and J. M. Sarrailh. Étude de l'influence du couvert naturel et de ses modifications a Madagascar. *Cahiers Scientifiques*, 4, 1974.

[16] R. Ballard and G.M. Will. Accumulation of organic matter and mineral nutrients under a *Pinus radiata* stand. *New Zealand Journal of Forestry Science*, 11(2):145–151, 1981.

[17] C.H. Banks and C. Kromhout. The effect of afforestation with *Pinus radiata* on summer baseflow and total annual discharge from Jonkershoek catchments. *For. S. Africa*, 3:43–65, 1963.

[18] N.F. Barros and R.M. Brandi. Effect of three forest species on the soil fertility of pasture land at Vicosa (Minas Gerais). *Brasil Florestal*, 6(21):24–29, 1974.

[19] R.E. Basher. Extreme wind gusts in Fiji. Information sheet 34, Fiji Meteorological Service, Nadi, Fiji, Oct 1985. Revision 1.

[20] R.E. Basher. Average relative humidity in Fiji. Information sheet 13, Fiji Meteorological Service, Nadi, Fiji, Aug 1986. Revision 1.

[21] R.E. Basher. Sea surface temperatures in Fiji waters. Information Sheet 105, Fiji Meteorological Service, Nadi, Fiji, Sep 1986.

[22] R.E. Basher. List of extreme wind gusts recorded in Fiji cyclones, 1964–1986. Information Sheet 106, Fiji Meteorological Service, Nadi, Fiji, Dec 1986.

[23] H.G. Bastable, W.J. Shuttleworth, R.L.G. Dallarossa, G. Fisch, and C.A. Nobre. Observations of climate, albedo and surface radiation over cleared and undisturbed Amazonian rainforest. *International Journal of Climatology*, 1993. Submitted.

[24] T.P. Bayliss-Smith. Rainfall, infiltration and runoff on Lakeba. In M. Latham and H.C. Brookfield, editors, *The Eastern Islands of Fiji: a Study of the Natural Environment, its Use and Man's Influence on its Evolution*, volume 162, pages 121–127. ORSTOM, UNESCO/UNFPA, MAB, Paris, 1983.

[25] F.J. Beekman. Energy balance and evapotranspiration for a 6.5-year-old *Pinus caribaea* plantation near Tulasewa, Fiji. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit Amsterdam, The Netherlands, 1992.

[26] J.P. Bell, T.J. Dean, and M.G. Hodnett. Soil moisture measurement by an improved capacitance technique, part II. Field techniques, evaluation and calibration. *Journal of Hydrology*, 93:79–90, 1987.

[27] B. Berg and H. Staaf. Leaching, accumulation and release of nitrogen in decomposing forest litter. In Clark F.E. and T. Rosswall, editors, *Invertebrate-Microbial Interactions*, page 349. Cambridge University Press, Cambridge, 1981.

[28] D.I. Bevege. In A.R. Ferguson, R.L. Bieleski, and I.B. Ferguson, editors, *Plant Nutrition 1978*, number 1 in 134, pages 53–60. N.Z. D.S.I.R, Wellington, 1978.

[29] D.I. Bevege and F.R. Humphreys. *Pinus caribaea*: Nutrition and soil studies. Consultancy report, Fiji Pine Commission, 1978.

[30] C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark. Automated ascorbic acid reduction method. In *Methods of Soil Analyses Part 2: Chemical and Microbiological Properties*, pages 1043–1044. American Society of Agronomy, Madison, Wisconsin, 1965.

[31] J.R. Blackie. The water balance of the Kimakia catchments. *East African Agricultural and Forestry Journal*, 43:155–174, 1979. Hydrological Research in East Africa, Special Issue.

[32] D.F. Boltz and M.G. Mellon. Spectrophotometric determination of phosphorus as molybdiphosphoric acid. *Analytical Chemistry*, 20(8):749–751, Aug 1948.

[33] M. Bonell and D.A. Gilmour. The development of overland flow in a tropical rainforest catchment. *Journal of Hydrology*, 39:365–382, 1978.

[34] M. Bonell, D.A. Gilmour, and D.F. Sinclair. Soil hydraulic properties and their effect on surface and subsurface water transfer in a tropical rainforest catchment. *Hydrological Science Bulletin*, 26:1–18, 1981.

[35] J.M. Bosch. Treatment effects on annual and dry period streamflow at Cathedral Peak. *South African Forestry Journal*, 108:29–38, 1979.

[36] J.M. Bosch. Streamflow response to catchment management in South Africa. *Proceedings Symposium on Hydrological Research Basins, Berne, Switzerland.*, 2:279–289, 1982.

[37] J.M. Bosch and J.D. Hewlett. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55:3–23, 1982.

[38] J.R. Bray and E. Gorham. Litter production in the forests of the world. *Advances in Ecological Research*, 2:101–157, 1964.

[39] R.G. Bray and L.T. Kurtz. Determination of total, organic and available forms of phosphorus in soils. *Soil Science*, 59:39–45, 1945.

[40] J. Bringfelt. Test of a forest evapotranspiration model. Meteorology and Climatology Reports 52, SMHI, Norrköpping, Sweden, 1986.

[41] L.A. Bruijnzeel. Immobilization of nutrients in plantation forests of *Pinus merkusii* and *Agathis dammara* growing on volcanic soils in Central Java. In A.T. Bachik and E. Pushparahja, editors, *Soils and Nutrition of Perennial Crops*, pages 19–29. Malaysian Soil Science Society, Kuala Lumpur, 1984.

[42] L.A. Bruijnzeel. Estimates of evaporation in plantations of *Agathis dammara* Warb. in South Central Java. *Journal of Tropical Science*, 1:145–161, 1988.

[43] L.A. Bruijnzeel. *Hydrology of Moist Tropical Forests and Effects of Conversion: A State-of-Knowledge Review.* UNESCO, Paris; Free University of Amsterdam, 1990.

[44] L.A. Bruijnzeel. Nutrient input – output budgets for tropical forest ecosystems: a review. *Journal of Tropical Ecology*, 7:1–24, 1991.

[45] L.A. Bruijnzeel. *Hydrological and Biogeochemical Aspects of Man-made forests in South central Java, Indonesia.* PhD dissertation, Vrije Universiteit van Amsterdam, Institute of Earth Sciences, Jan 1983.

[46] L.A. Bruijnzeel. Nutrient content of bulk precipitation in South-Central Java, indonesia. *Journal of Tropical Ecology*, 5:187–202, 1989.

[47] L.A. Bruijnzeel. Managing tropical forest watersheds for production: Where contradictory theory and practice co-exist. In F.R. Miller and K.L. Adam, editors, *Wise Management of Tropical Forests*, pages 37–75. Oxford Forestry Institute, Oxford, 1992.

[48] L.A. Bruijnzeel. The chemical mass balance of a small basin in a wet monsoonal environment and the effect of fast-growing plantation forest. In *Dissolved loads of Rivers and Surface Water Quantity/Quality Relationships*, number 141 in IAHS Publication, pages 229–239, Institute of Hydrology, Wallingford, UK, Aug 1983. International Association of Hydrological Sciences, IAHS Press.

[49] L.A. Bruijnzeel. Deforestation and dry season flow in the tropics, a closer look. *Journal of Tropical Forest Science*, 1:229–243, 1989.

[50] L.A. Bruijnzeel. Sustainability of fast-growing plantation species in the humid tropics, including nutritional aspects. In C.F. Jordan *et al.*, editor, *Taungya: Forest Plantations with Agriculture in Southeast Asia*, pages 51–67. Commonwealth Agricultural Bureaux, Wallingford, U.K., 1992.

[51] L.A. Bruijnzeel and K.F. Wiersum. A nutrient balance sheet for *Agathis dammara* Warb. plantation forest under various management conditions in Central Java, Indonesia. *Forest Ecology and Management*, 10:195–208, 1985.

[52] L.A. Bruijnzeel and K.F. Wiersum. Rainfall interception by a young *Acacia auriculiformis* (A. Cunn) plantation forest in West Java, Indonesia: Application of Gash's analytical model. *Hydrological Processes*, 1:309–319, 1987.

[53] H.A.R. de Bruin. *The energy balance of the earth's surface: a practical approach.* PhD dissertation, Agricultural University Wageningen, The Netherlands, 1982.

[54] H.A.R. de Bruin, N.J. Bink, and L.J.M. Kroon. Fluxes in the surface layer under advective conditions. In T. J. Schmugge and J. C. André, editors, *Land Surface Evaporation*, chapter 9, pages 157–169. Springer-Verlag, New York, first edition, 1991.

[55] H.A.R. de Bruin, W. Kohsiek, and B.J.J.M. van den Hurk. A verification of some methods to determine the fluxes of momentum, sensible heat, and water vapour using standard deviation and structure parameter of scalar meteorological quantities. *Boundary Layer Meteorology*, 63:231–257, 1993.

[56] H.A.R. de Bruin and C.J. Moore. Zero-plane displacementand roughness length for tall vegetation, derived from a simple mass conservation hypothesis. *Boundary-Layer Meteorology*, 31:39–49, 1985.

[57] W.H. Brutsaert. *Evaporation into the Atmosphere*. D. Reidel Publishing Company, Dordrecht, The Netherlands, 1982.

[58] A. Burgess. The release of cations during the decomposition of forest litter. *Transactions of the 6^{th} international Congress on Soil Science B*, pages 741–745, 1956.

[59] T.B.A. Burghouts. *Spatial Heterogeneity of Nutrient Cycling in Bornean Rain Forest.* PhD dissertation, Vrije Universiteit, Amsterdam, Oct 1993.

[60] T.P. Burt. An automatic fluid-scanning switch tensiometer system. Technical bulletin, British Geomorphological Research Group, Norwich, UK, 1978.

[61] R.J. Buschbacher. *Changes in Productivity and Nutrient Cycling Following Conversion of Amazonian Rainforest to Pasture.* PhD dissertation, University of Georgia, Athens, Georgia, 1984.

[62] R.J. Buschbacher. Tropical deforestation and pasture development. *BioScience*, 36:22–28, 1986.

[63] I.R. Calder. Do trees use more water than grass? *Water Services*, 1979.

[64] I.R. Calder. Forest evaporation. In Anonymous, editor, *Hydrological Processes of Forested Areas*, pages 173–193. National Research Council of Canada Publication No. 20584, Ottawa, 1982.

[65] I.R. Calder. *Evaporation in the Uplands.* J. Wiley & Sons Ltd. UK, 1990.

[66] I.R. Calder, R.J. Harding, and P.T.W. Rosier. An objective assessment of soil-moisture deficit models. *Journal of Hydrology*, 60:329–355, 1983.

[67] I.R. Calder, I.R. Wright, and D. Murdiyarso. A study of evaporation from tropical rainforest — West Java. *Journal of Hydrology*, 89:13–31, 1986.

[68] C.R. Carden. Estimates of total aboveground biomass for a typical 15-year old *Pinus caribaea* plantation in Fiji. Draft report, Fiji Pine Commission, 1979.

[69] M.L. Carey, I.R. Hunter, and I. Andrew. *Pinus radiata* forest floors: Factors affecting organic matter and nutrient dynamics. *New Zealand Journal of Forestry Science*, 12(1):36–48, 1982.

[70] P.S. Chen, T.Y. Toribora, and H. Warner. Microdetermination of phosphorus. *Analytical Chemistry*, 28:1756–1758, 1956.

[71] R. Chhabra, J.L. Pleysier, and A. Cremers. The measurement of the cation exchange capacity and exchangeable bases in soils : a new method. In *Proceedings of the International Clay Conference*, pages 439–449, Mexico, 75.

[72] L.S. Chia. Sunshine and solar radiation in Singapore. In J.B. Oci and L.S. Chia, editors, *The Climate of West Malaysia and Singapore*, pages 48–56. Oxford University Press, Singapore, 1974.

[73] E.O. Chijioke. Impact on soils of fast growing species in lowland humid tropics. Forestry Paper 21, FAO, 1980.

[74] R.M. Cionco. A mathematical model of air flow in a vegetative canopy. *Journal of Applied Meteorology*, 4:517–522, 1965.

[75] A. Claeson, H.I. Manner, and K. Nakatani. Regression analysis of the above-ground biomass of Fijian plantation *Pinus caribaea* var. *hondurensis. South Pacific Journal of Natural Science*, 5:46–59, 1984.

[76] J.L. Clayton. Nutrient supply to soil by rock weathering. In A.L. Leaf, editor, *Proceedings of the Symposium on Impacts of Intensive Harvesting on Forest Nutrient Cycling*, pages 75–96, Ithaca, New York, 1979. New York State University.

[77] G.R. Cochrane. Problems of vegetation change in Western Viti Levu. In F. Gale and C.G. Lowton, editors, *Settlement and Encounter: Geographical Studies Presented to Sir Grenfell Price*, pages 115–147. Oxford University Press, Melbourne, 1969.

[78] J. Conover. *Practical Nonparametric Statistics.* John Wiley and Sons, New York, 2 edition, 1980.

[79] J.D. Cooper. Water use of a tea estate from soil moisture measurements. *East African Agricultural and Forestry Journal*, 43:102–121, 1979.

[80] I.S. Cornforth. Reafforestation and nutrient reserves in the humid tropics. *Journal of Applied Ecology*, 7:609–615, 1970.

[81] J.D. Coulter. Climatological summary: Nadrau climate station. Information Sheet 100, Fiji Meteorological Service, Nadi, Fiji, May 1984.

[82] J.D. Coulter. Mean temperature and atmospheric pressure at Nadi Airport and Nausori Airport. Information Sheet 63, Fiji Meteorological Service, Nadi, Fiji, Oct 1981.

[83] J.D. Coulter. Rainfall quintiles for selected Fiji stations. Information Sheet 62, Fiji Meteorological Service, Nadi, Fiji, Dec 1981.

[84] J.D. Coulter. Average number of raindays at Fiji stations. Information Sheet 70, Fiji Meteorological Service, Nadi, Fiji, Dec 1981.

[85] D.J. Cown, D.L. McConchie, and G.D. Young. Wood properties of *Pinus caribaea* var. *hondurensis* grown in Fiji. FRI Bulletin 17, Forest Research Institute, New Zealand Forest Service, Private Bag, Rotorua, New Zealand, 1983.

[86] E. Cuevas, S. Brown, and A.E. Lugo. Above- and below-ground organic matter storage and production in a tropical pine plantation and a paired broadleaf secondary forest. *Plant and Soil*, 135:257–268, 1991.

[87] A.M. Dano. Effect of burning and reforestation on grassland watersheds in the Philippines. *IAHS Publication*, 192:53–61, 1990.

[88] T.J. Dean, P.J. Bell, and A.J.B. Baty. Soil moisture measurement by an improved capacitance technique, part I. Sensor design and performance. *Journal of Hydrology*, 93:67–78, 1987.

[89] A.C.C.P. Dias and S. Northcliff. Effects of tractor passes on the physical properties of an Oxisol in the Brazilian Amazon. *Tropical Agriculture*, 62:137–141, 1985.

[90] A.C.C.P. Dias and S. Northcliff. Effects of two land clearing methods on the physical properties of an Oxisol in the Brazilian Amazon. *Tropical Agriculture*, 62:202–212, 1985.

[91] W.T. Dickinson and H. Whiteley. Watershed areas contributing to runoff. *IAHS publication*, 96:12–26, 1970.

[92] I. Douglas, T. Spencer, Kawi Bidin, W. Sinun, and W.M. Wong. The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama rain forest, Sabah, Malaysia. *Philosophical Transactions of the Royal Society*, 335:397–406, 1992. Series B.

[93] J.E. Douglas and W.T. Swank. Effects of management practices on water quality and quantity. Proceedings of the municipal watershed symposium, forest service technical report ne-13, USDA, Upper Darby, PA, USA, 1975.

[94] J.I. Drever. *The Geochemistry of Natural Waters.* Prentice-Hall, Inc., USA, 1982.

[95] R. van den Driessche. Prediction of mineral nutrient status of trees by foliar analysis. *Botanical Review*, 40:347–394, 1974.

[96] P.J. Drysdale and T.T. Rawaqa. Catchment research in Fiji and the Fiji Pine Commission. Paper presented at the Taiwan Workshop, 1987.

[97] R.A. Duce and E.J. Hoffman. Chemical fractionation at the air–sea interface. *Annual Review of the Earth Planetary Science*, 4:187–228, 1976.

[98] P. Duchaufour. *Pedology: Pedogenesis and Classification.* George Allen & Unwin, London, 1982.

[99] T. Dunne. Field studies of hillslope flow processes. In M.J. Kirby, editor, *Hillslope Hydrology.* J. Wiley and Sons, New York, 1978.

[100] K.A. Edwards. The water balance of the Mbeya experimental catchments. *East African Agricultural and Forestry Journal*, 43:231–247, 1979. Hydrological Research in East Africa, Special Issue.

[101] C.W.O. Eeles. Soil moisture deficits under bamboo forest, pine plantations and grass. *East African Agricultural and Forestry Journal*, 43:179–187, 1979. Hydrological Research in East Africa, Special Issue.

[102] N. Eernisse. Relative depths of weathering front and fine root network: A pilot study, Mabura Hill, Guyana. Tropenbos programme Guyana, Tropenbos Foundation, Wageningen, The Netherlands, 1993.

[103] J.K. Egunjobi. Dry matter production by an immature stand of *Pinus caribaea* in Nigeria. *Oikos*, 26(1):80–85, 1975.

[104] J.K. Egunjobi. An evaluation of five methods for estimating biomass of an even-aged plantation of *Pinus caribaea* L. *Ecology and Plant*, 11:109–116, 1976.

[105] J.K. Egunjobi and S.A. Bada. Biomass and nutrient distribution in stands of *Pinus caribaea* L. in the dry forest zone of Nigeria. *Biotropica*, 11(2):130–135, 1979.

[106] J.K. Egunjobi and F.E. Fasehun. Preliminary observations on the monthly litter-fall and nutrient content of *Pinus caribaea* L. litter. *Nigerian Journal of Science*, 6(1):109–116, Jul 1972.

[107] J.K. Egunjobi and B.S. Onweluzo. Litter fall, mineral turnover and litter accumulation in *Pinus caribaea* L. stands at Ibadan, Nigeria. *Biotropica*, 11(4):251–255, 1979.

[108] E. Eriksson. The yearly circulation of chlorine and sulphur in nature. Part 2. Meteorological, geochemical and pedological implications. *Tellus*, 12(1):63–109, 1960.

[109] J. Evans. *Plantation Forestry in the Tropics.* Clarendon Press, Oxford, 1992.

[110] FAO. Guidelines for soil profile description. Manual, FAO, Rome, 1977.

[111] R.F. Fisher. Impact of intensive silviculture on soil and water quality in a coastal lowland. In R. Lal and E.W. Russell, editors, *Tropical Agricultural Hydrology*, chapter 4, pages 299–309. J. Wiley and Sons Ltd., 1981.

[112] A. Focan and J.J. Fripiat. Une année d'observation de l'humidité du sol à Yangambi. Bulletin des Sèances 24, Institut Royal Colonial Belge, 1953.

[113] F.C. Ford-Robertson. *Terminology of Forest Science, Technology Practice and Products.* Society of American Foresters, 1971. English language version.

[114] M.C. Forti and C. Neal. Hydrochemical cycles in tropical rainforest: an overview with emphasis on Central Amazonia. *Journal of Hydrology*, 134:103–115, 1992.

[115] J.L. Frangi and A.E. Lugo. Hurricane damage to a flood plain forest in the Luquillo mountains of Puerto Rico. *Biotropica*, 23(4):324–335, 1991. Special Issue.

[116] J.M. Fritsch. Les effets du défrichement de la forêt Amazonienne et de la mise en culture sur l'hydrologie de petits bassins versants. Technical report, Institute Francais de Recherche Scientifique pour le Développement en Coopération, 1992. Editions de l'ORSTOM, Collection ÉTUDES et THÈSES.

[117] K.F.A. Frumau. Aerodynamic characteristics and evapotranspiration of a young *Pinus caribaea* plantation forest near Tulasewa, Fiji. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit van Amsterdam, The Netherlands, 1993.

[118] J.F. Gabites. Mean hourly relative humidities at Nadi. Information Sheet 19, Fiji Meteorological Service, Nadi, Fiji, Aug 1977.

[119] J.F. Gabites. Solar radiation in Fiji. Information Sheet 29, Fiji Meteorological Service, Nadi, Fiji, Jun 1978.

[120] R.L. Gadgil and P.D. Gadgil. Influence of clearfelling on decomposition of *Pinus radiata* litter. *New Zealand Journal of Forestry Science*, 8(2):213–224, 1978.

[121] J.R. Garratt. Aerodynamic roughness and mean monthly surface stress over Australia. Technical Paper 29, CSIRO Australian Division of Atmospheric Physics, 1977.

[122] J.H.C. Gash. An analytical model of rainfall interception by forests. *Quarterly Journal of the Royal Meteorological Society*, 105:43–55, 1979.

[123] J.H.C. Gash and A.J. Morton. An application of the Rutter model to the estimation of the interception loss from Thetford forest. *Journal of Hydrology*, 38:49–58, 1978.

[124] J.H.C. Gash, I.R. Wright, and C.R. Lloyd. Comparative estimates of interception loss from three coniferous forests in Great Brittain. *Journal of Hydrology*, 48:89–105, 1980.

[125] M.T. van Genuchten. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44:892–898, 1980.

[126] M. George. *Organic Productivity and Nutrient Cycling in Eucalyptus Hybrid Plantations*. PhD dissertation, Meerut University, Meerut, Sep 1977.

[127] H.L. Gholz, R.F. Fisher, and W.L. Pritchett. Nutrient dynamics in slash pine plantation ecosystems. *Ecology*, 66(3):647–659, 1985.

[128] H.M. Ghulam and I. Norhayati. Long term effects of forest clearing on hydrology and top soil properties. Paper presented at the FRIM-IHP-UNESCO Regional Seminar on Tropical Forest Hydrology, Kuala Lumpur, Malaysia, Sep 1989.

[129] B.S. Ghuman and R. Lal. A report to UNU. Mimeo, IITA, Ibadan, Nigeria, 1985.

[130] G.P. Gillman, D.F. Sinclair, R. Knowlton, and M.G. Keys. The effect on some soil chemical properties of the selective logging of a North Queensland rainforest. *Forest Ecology and Management*, 12:195–214, 1985.

[131] R.E. Goddard and C.A. Hollis. The genetic basis of forest tree nutrition. In G.D. Bowen and E.K.S. Nambiar, editors, *Nutrition of Forest Trees in Plantations*, chapter 9, pages 237–258. Academic Press Inc., London, 1984.

[132] J.R. Gosz. Biological factors influencing nutrient supply in forest soils. In G.D. Bowen and E.K.S. Nambiar, editors, *Nutrition of Forest Trees in Plantations*, pages 119–146. Academic Press Inc. Ltd., London, 1984.

[133] W.M. Gray. Global view of the origin of tropical disturbances and storms. *Monthly Weather Reviews*, 96:55–73, 1968.

[134] W.M. Gray. Environmental influences on tropical cyclones. *Australian Meteorological Magazine*, 36:127–139, 1988.

[135] A. Greenberg, J. Connors, and D. Jenskin. *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington, 1980.

[136] K.J. Gregory and D.E. Walling. *Drainage Basin: Form and Process*. Edward Arnold Ltd., U.K., 1973.

[137] B. Gunadi. Litterfall, litter turnover and soil respiration in two pine forests plantations in Central Java, Indonesia. *Journal of Tropical Forest Science*, 1993. In press.

[138] B. Gunadi. *Decomposition and Nutrient Flow in a Pine Forest Plantation in Central Java*. PhD dissertation, Vrije Universiteit te Amsterdam, The Netherlands, Sep 1993.

[139] B. Gunadi and H.A. Verhoef. Seasonal dynamics of decomposition along the slope of a pine forest in Central Java. *Journal of Tropical Ecology*, 1993. In press.

[140] B.L. Haines, J.B. Waide, and R.L. Todd. Soil solution nutrient concentrations sampled with tension and zero-tension lysimeters: Report of discrepancies. *Soil Science Society of America Journal*, 46(3):658–661, 1982.

[141] F.R. Hall. Baseflow recessions – a review. *Water Resources Research*, 4:973–982, 1968.

[142] R.J. Hanks and G.L. Ashcroft. *Applied Soil Physics*. Springer, 1980.

[143] E.A. Hansen and A.R. Harris. Validity of soil-water samples collected with porous ceramic cups. *Soil Science Society of America Proceedings*, 39:528–536, 1975.

[144] E. Harkema. Evaporation for a 16-year-old *Pinus caribaea* plantation and for a natural grassland in the Nabou Forest Estate, Fiji. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit Amsterdam, The Netherlands, 1993.

[145] H. Hase and H. Fölster. Bioelement inventory of a tropical (semi)-evergreen seasonal forest on eutrophic alluvial soils, Western Llanos, Venezuela. *Oecologia Plantarum*, 17:331–346, 1982.

[146] H. Hase and H. Fölster. Impact of plantation forestry with teak *Tectona grandis* on the nutrient status of young alluvial soils in West Venezuela. *Forest Ecology and Management*, 6:33–57, 1983.

[147] B. Hathway and H. Colley. Eocene to miocene geology of Southwest Viti Levu. In P.F. Ballance, R.H. Herzer, and T.A. Vallier, editors, *Tonga-Lau II*, Earth Science Series. Circum-Pacific Counsel for Energy and Mineral Resources, 1989. in press.

[148] J.D. Helvey and J.H. Patrick. Canopy and litter interception of rainfall by hardwoods of Eastern United States. *Water Resources Research*, 1:193–205, 1965.

[149] J.D. Hem. Study and interpretation of the chemical characteristics of natural water. Water Supply Paper 1373, U.S. Geological Survey, 1970. 2^{nd} edition.

[150] A. Hendrikson and A.R. Selmer-Olsen. Automatic methods for determination of nitrate and nitrite in water and soil extracts. *Analyst*, 95:514–518, 1970.

[151] S.R. Herwitz. Episodic stemflow inputs of magnesium and potassium to a tropical forest floor during heavy rainfall events. *Oecologia*, 70:423–425, 1986.

[152] J.H.R. Heuch. A preliminary site index for *Pinus caribaea* in Fiji. Research Paper 15, Fiji Pine Limited, P.O. Box 621, Lautoka, Fiji, 1992.

[153] H.D. Hewlett, H.E. Post, and R. Doss. Effect of clear-cut silviculture on dissolved ion export and water yield in the piedmont. *Water Resources Research*, 20(7):1030–1038, 1984.

[154] J.D. Hewlett and J.C. Fortson. The paired catchment experiment. In J.D. Hewlett, editor, *Forest water Quality*, pages 11–14. School of Forest Resources, University of Georgia, Athens, GA, USA, 1983.

[155] J.D. Hewlett and A.R. Hibbert. Factors affecting the response of small watersheds to precipitation in humid areas. In W.E. Sopper and H.W. Lull, editors, *International Symposium on Forest Hydrology*, pages 275–290. Pergamon Press, Oxford, UK, 1967.

[156] B.B. Hicks. Application of forest canopy – atmosphere turbulent exchange information. In B.A. Hutchinson and B.B. Hicks, editors, *The Forest – Atmosphere Interaction*, pages 631–644. D. Reidel Publishing Company, Dordrecht, The Netherlands, 1985.

[157] R.E. Horton. The role of infiltration in the hydrological cycle. *Transactions of the American Geophysical Union*, 14:446–460, 1933.

[158] V.J.G. Houba, J.J. van der Lee, I. Novozamsky, and I. Walinga. Soil and plant analysis. Part 5: Soil analyses procedures. Chapter 10, Wageningen Agricultural University, 1989.

[159] R.E. Houtz. Regional geology of Lomawai–Momi, Nandronga, Viti Levu. Geological Survey of Fiji Bulletin 3, Geological Survey Department, Suva, Fiji, 1959.

[160] Y.J. Hsia. Changes in storm hydrographs after clearcutting a small hardwood forested watershed in central Taiwan. *Forest Ecology and Management*, 20:117–134, 1987.

[161] J. Hudson, M. Kellman, K. Sanmugadas, and C. Alvarado. Prescribed burning of *Pinus oocarpa* in Honduras. I. Effects on surface runoff and sediment loss. *Forest Ecology and Management*, 5:269–281, 1983.

[162] J. Hudson, M. Kellman, K. Sanmugadas, and C. Alvarado. Prescribed burning of *Pinus oocarpa* in Honduras. II. Effects on nutrient cycling. *Forest Ecology and Management*, 5:283–300, 1983.

[163] R.W.A. Hutjes, A. Wierda, and A.W.L. Veen. Rainfall interception in the Tai forest, Ivory Coast: Application of two simulation models to a humid tropical system. *Journal of Hydrology*, 114:259–275, 1990.

[164] M.A. Ibrahim and M.T. Chang. On the calibration of forested watersheds: Single *versus* paired watershed approaches. Paper presented at the FRIM-IHP-UNESCO Regional Seminar on Tropical Forest Hydrology, Kuala Lumpur, Sep 1989. 21 pages.

[165] D.E. Iyamabo. Effects of *Pinus caribaea* on basaltic soil in Miango, Jos plateau, Nigeria. *Research Paper (Savanna Series)*, 22:9, 1973.

[166] I.J. Jackson. Relationships between rainfall parameters and interception by tropical forests. *Journal of Hydrology*, 24:215–238, 1975.

[167] M.L. Jackson. *Soil Chemical Analysis*. Prentice Hall, Englewood Cliffs, N.J., 1958.

[168] R. Jamet. Evolution des principales caracteristiques des sols de reboisements de Loudima, Congo. Cahiers ORSTOM Series Pedologie 13, ORSTOM, France, 1975. Chapters 3 and 4.

[169] P.G. Jarvis, G.B. James, and J.J. Landsberg. Coniferous forest. In J.L. Monteith, editor, *Vegetation and the Atmosphere Volume 2. Case Studies*, chapter 12, pages 171–240. Academic Press, London, 1976.

[170] V. Jetten. *Modelling the Effects of Logging on the Water Balance of a Tropical Rain Forest.* PhD dissertation, University of Utrecht, Department of Physical Geography, March 1994.

[171] N.M. Johnson, G.E. Likens, F.H. Bormann, and R.S. Pierce. Rate of chemical weathering of silicate minerals in New Hampshire. *Geochimica et Cosmochimica Acta*, 32:531–545, 1968.

[172] B. de Jong. Net radiation received by a horizontal surface at the earth. Delft University Press, 1973.

[173] C.F. Jordan. Shifting cultivation. case study no. 1. Slash and burn agriculture near San Carlos, Rio Negro, Venezuela. In C.F. Jordan, editor, *Amazonian Rain Forests. Ecosystem Disturbance and Recovery.*, pages 9–23. Springer, New York, 1987.

[174] C.F. Jordan. Are process rates higher in tropical forest ecosystems? In J. Proctor, editor, *Mineral Nutrients in Tropical Forests and Savanna Ecosystems*, pages 205–215. Blackwell Scientific Publications, London, 1989.

[175] Kamaruzaman Jusoff. Effect of tracked and rubber-tyred logging machines on soil physical properties of the Berkelah Forest Reserve, Malaysia. *Pertanika*, 14(3):265–276, 1991.

[176] O. Kadeba. Above-ground biomass production and nutrient accumulation in an age sequence of *Pinus caribaea* stands. *Forest and Ecological Management*, 41:237–248, 1991.

[177] O. Kadeba and E.A. Aduayi. Litter production, nutrient recycling and litter accumlation in *Pinus caribaea* Morelet var. *hondurensis* stands in the northern Guinea savanna of Nigeria. *Plant and Soil*, 86:197–206, 1985.

[178] D. Kammer and R. Raj. Preliminary estimates of minimum flows in Varaciva creek, Ba province, and the effect of afforestation on water resources. Technical Note 79/1, Public Works Department, Suva, Fiji, 1979.

[179] M.R. Kaufmann and C.A. Troendle. The relationship of leaf area and foliage biomass to sapwood conducting area in four subalpine forest tree species. *Forest Science*, 27(3):477–482, 1981.

[180] M. Kellman. Mineral nutrient dynamics during savanna-forest transformation in Central America. In J. Proctor, editor, *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*, pages 137–151. Blackwell Scientific Publications, London, 1989.

[181] J. Kessler and R.J. Oosterbaan. Determining hydraulic conductivity of soils. In *I.L.R.I. Publication no. 16. Volume III.*, pages 253–296. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 1973.

[182] P.H. Khanna and B. Ulrich. Soil characteristics influencing nutrient supply in forest soils. In G.D. Bowen and E.K.S. Nambiar, editors, *Nutrition of Forest Trees in Plantations*, chapter 4, pages 79–117. Academic Press Inc., London, 1984.

[183] J.W. Kijne. Determining evapotranspiration. In *Drainage Principles and Applications. Part III. Surveys and Investigations.*, chapter 19, pages 53–111. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 1974.

[184] J.P. Kimmins. *Forest Ecology.* MacMillan Publishing Company, New York, 1987.

[185] D.G. Kleinbaum and L.L. Kupper. *Applied Regression Analysisand other Multivariable Methods.* PWS-Kent Publishing Company, Boston, 1978.

[186] R. Krishna. Mean hourly temperatures at Nadi Airport. Information Sheet 18, Fiji Meteorological Service, Nadi, Fiji, Nov 1981. Revised.

[187] M. Krom. Spectrophotometric determination of ammonia: a study of a modified Berthelot reaction using salicylate and dichloroisocyanurate. *Analyst*, 105:305–316, 1980.

[188] F. Kuik. *Single scattering of light by ensembles of particles with various shapes.* PhD dissertation, Vrije Universiteit van Amsterdam, Department of Physics, 1992.

[189] H.S. Ladd. *Geology of Viti Levu*, volume 119 of *Bernice P. Bishop Museum Bulletin.* The Museum, Honolulu, Hawaii, first edition, May 1934.

[190] R. Lal. *Tropical Ecology and Physical Edaphology.* John Wiley & Sons Ltd., UK, 1987.

[191] R. Lal and D.J. Cummings. Clearing a tropical forest I. Effects on soil and micro-climate. *Field Crops Res.*, 2:91–107, 1979.

[192] D. Lamb. Variations in the foliar concentrations of macro and micro elements in a fast-growing tropical eucalypt. *Plant Soil*, 45:477–492, 1976.

[193] J.R. Landon. *Booker Tropical Soil Manual.* Longman Inc., New York, 1984.

[194] J.P. Lanly, K.D. Singh, and K. Janz. FAO's 1990 reassessment of tropical forest cover. *Nature and Resources*, 27(2):21–26, 1991.

[195] M. Latham. Evolution of the environment after the reafforestation of *talasiga* areas. In M. Latham and H.C. Brookfield, editors, *The Eastern Islands of Fiji: a Study of the Natural Environment, its Use and Man's Influence on its Evolution*, volume 162, pages 143–151. ORSTOM, UNESCO/UNFPA, MAB, Paris, 1983.

[196] A.L. Leaf. Plant analysis as an aid in fertilizing forests. In L.M. Walsh and J.D. Beaton, editors, *Soil Testing and Plant Analysis*, pages 427–454. Soil Science Society of America, Madison, Wisconsin, 1973.

[197] R. Lee. Theoretical estimates *versus* forest water yield. *Water Resources Research*, 6:1327–1334, 1970.

[198] R.E. Leonard. Mathematical theory of interception. In W.E. Sopper and H.W. Lull, editors, *International Symposium on Forest Hydrology*, pages 131–136. Pergamon Press, Oxford, 1967.

[199] P.R. Leopoldo, A. de Pádua Sousa, and S.T. Filho. Interceptação da áqua de chuva em cultura de cana-de-açúcar. *Brasil Açcareiro*, 6:9–16, 1981.

[200] D.M. Leslie, K. Nakatani, T. Tora, R.A. Prasad, and R.J. Morrison. Soils of the Fiji pine forests. Part 2; Soils of the Nabou forest. Environmental Studies Report 25, Institute of Natural Resources, University of the South Pacific, 1985.

[201] L. Leyton, E.R.C. Reynolds, and F.B. Thompson. Rainfall interception in forest and moorland. In W.E. Sopper and H.W. Lull, editors, *International Symposium on Forest Hydrology*, pages 163–178. Pergamon Press, Oxford, 1967.

[202] G.E. Likens, F.H. Bormann, R.S. Pierce, J.S. Eaton, and N.M. Johnson. *Biogeochemistry of a Forested Catchment.* Springer-Verlag, New York, 1977.

[203] W.S. van Lill, F.J. Kruger, and D.B. van Wijk. The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. *Journal of Hydrology*, 48:107–118, 1980.

[204] S.N. Little and G.O. Clock. The influence of residue and prescribed fire on distributions of forest nutrients. Research Paper PWN 338, USDA Forest Service, 1985.

[205] C.R. Lloyd, A.D. Culf, A.J. Dolman, and J.H.C. Gash. Estimates of sensible heat flux from observations of temperature fluctuations. *Boundary-Layer Meteorology*, 57:311–322, 1991.

[206] C.R. Lloyd, J.H.C. Gash, W.J. Shuttleworth, and A. de O. Marques-Filho. The measurement and modelling of rainfall interception by Amazonian rainforest. *Journal of Hydrology*, 43:277–294, 1988.

[207] C.R. Lloyd and A. de O. Marques-Filho. Spatial variability of throughfall and stemflow measurements in the Amazonian rain forest. *Agriculture and Forest Meteorology*, 42:63–73, 1988.

[208] J.D. Lodge, F.N. Scatena, C.E. Asbury, and M.J. Sánchez. Fine litterfall and related nutrient inputs resulting from hurricane Hugo in subtropical wet and lower montane rain forests of Puerto Rico. *Biotropica*, 23(4):336–342, 1991. Special Issue.

[209] A.E. Lugo. Comparison of tropical tree plantations with secondary forests of similar age. *Ecological Monographs*, 62(1):1–41, 1992.

[210] B. Lundgren. Soil conditions and nutrient cycling under natural and plantation forests in Tanzanian highlands. Reports in Forest Ecology and Forest Soils 31, Swedish University of Agricultural Sciences, Uppsala, 1978.

[211] H.J. Lutz and R.F. Chandler Jr. *Forest Soils.* John Wiley and Sons, New York, 1946.

[212] H.A.I. Madgwick. Above-ground weight of forest plots — comparison of seven methods of estimation. *New Zealand Journal of Forest Science*, 13(1):100–107, 1983.

[213] J. Maggs. Mineral cycling in *Pinus caribaea* ecosystems. Australian Forest Research Newsletter, 1979-1980 6, CSIRO Division of Forest Research, Canberra, 1981.

[214] A. Malmer. *Dynamics of Hydrology and Nutrient Losses as Response to Establishment of Forest Plantation: A Case Study on Tropical Rainforest Land in Sabah, Malaysia.* PhD dissertation, Swedish University of Agricultural Sciences, Faculty of Forestry, S-901 83 Umeå, Sweden, 1993.

[215] A. Malmer and H. Grip. Soil disturbance and loss of infiltrability caused by mechanized and manual extraction of tropical rainforest in Sabah, Malaysia. *Forest Ecology and managemnt*, 38:1–12, 1990.

[216] D.W. Marquardt. An algorithm for least squares estimation of non-linear parameters. *Society of Industrial Applications of Mathematics*, 11(2):431–441, 1963.

[217] J.H. McCaughey. Energy balance storage terms in a mature mixed forest at Petawawa, Ontario – a case study. *Boundary Layer Meteorology*, 31:89–101, 1985.

[218] J.H. McCaughey and W.L. Saxton. Energy balance storage terms in a mixed forest. *Agricultural Forestry and Meteorology*, 44:1–18, 1988.

[219] A.L.C. McWilliam, J.M. Roberts, O.M.R. Cabral, M.V.B.R. Leitao, A.C.L. da Costa, G.T. Maitelli, and C.A.G.P. Zamparoni. Leaf area index and above-ground biomass of *terra firme* rainforest and adjacent clearings in Amazonia. *Functional Ecology*, 1993. In Press.

[220] D.J. Mead. Diagnosis of nutrient deficiencies in plantations. In G.D. Bowen and E.K.S. Nambiar, editors, *Nutrition of Forest Trees in Plantations*, chapter 10, pages 259–291. Academic Press Inc., London, 1984.

[221] H.G. Miller. Dynamics of nutrient cycling in plantations ecosystems. In G.D. Bowen and E.K.S. Nambiar, editors, *Nutrition of Forest Trees in Plantations*, chapter 3, pages 53–78. Academic Press Inc., London, 1984.

[222] H.G. Miller, J.M. Cooper, and J.D. Miller. Effect of nitrogen supply on nutrients in litterfall and crown leaching in a stand of Corsican pine. *Journal of Applied Ecology*, 13:233–248, 1976.

[223] H.G. Miller, J.D. Miller, and J.M. Cooper. *Canadian Journal of Forest Research*, 9:563–572, 1981.

[224] E.C.J. Mohr, F.A. van Baren, and J. van Schuylenborgh. *Tropical Soils.* Mouton-Ichtiar Baru-Van Hoeven, The Hague, Paris, Jakarta, 1972.

[225] L.C.B. Molion and C.J. Moore. Estimating the zero-plane displacement for tall vegetation using a mass conservation method. *Boundary-Layer Meteorology*, 26:115–125, 1983.

[226] A.S. Monin and A.M. Yaglom. *Statistical Fluid Mechanics: Mechanics of Turbulence*, volume 1. M.I.T. Press, Cambridge, 1971. Translation editor: L.J. Lumley.

[227] J.L. Monteith. Evaporation and the environment. Symposium of the Society of Experimental Biology no. 19, 1965.

[228] J.L. Monteith. *Vegetation and the Atmosphere. Volume 2: Case Studies.* Academic Press, London, 1976.

[229] J.L. Monteith. Theory and performance of a dynamic diffusion porometer. *Agriculture and Forest Meteorology*, 44:27–38, 1988.

[230] B. Montény and G. Gosse. Analyse et estimation du rayonnement net d'une culture de *Panicum maximum* en zone tropicale humide. *Oecologia Plantarum*, 11(2):173–191, 1976.

[231] R.P.C. Morgan. *Soil Erosion and Conservation.* Longman, Harlow, UK, 1986.

[232] R.J. Morrison and W.C. Clarke. Erosion and sedimentation in Fiji - an overview. In R.R. Ziemer, C.L. O'Loughlin, and L.S. Hamilton, editors, *Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Steeplands (Proceedings of the Fiji Symposium*, number 192 in IAHS-AISH Publication, pages 14–23, Institute of Hydrology, Wallingford, UK, Jun 1990. International Association of Hydrological Sciences, IAHS Press.

[233] R.J. Morrison and Dandy. The effect of shaking time on the soil phosphorus extract by the Fiji Department of Agriculture sulphuric acid method. *Fiji Agricultural Journal*, 41:113–114, 1979.

[234] Y. Mualem. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12:513–522, 1976.

[235] D. Mueller-Dombois and J.C. Goldammer. Fire in tropical ecosystems and global environmental change: An introduction. In J.C. Goldammer, editor, *Fire in the Tropical Biota*, number 84 in Ecological Studies, chapter 1, pages 1–10. Springer-Verlag, Heidelberg, 1990.

[236] R. Nakamura. Runoff analysis by electrical conductance of water. *Journal of Hydrology*, 14:197–212, 1971.

[237] J.E. Nash. The form of the instantaneous unit hydrograph. *International Association of Hydrology General Assembly*, 3:114–121, 1957.

[238] J.E. Nash. Systemeatic determination of unit hydrograph parameters. *Journal of Geophysical Research*, 64:111–115, 1959.

[239] Nicholson. FRI Bulletin 70, Forest Research Institute, Rotorua, New Zealand, 1984.

[240] S. Nortcliff and J.B. Thornes. Variations in soil nutrients in relation to soil moisture status in a tropical forested ecosystem. In J. Proctor, editor, *Mineral Nutrient in Tropical Forest and Savanna Ecosystems*, pages 137–151. Blackwell Scientific Publications, London, 1989.

[241] P.H. Nye and D.J. Greenland. The soil under shifting cultivation. Technical Communication 51, Commonwealth Bureau of Soils, Harpenden, Commonwealth Agricultural Bureaux, Farnham Royal, Bucks, UK, 1960.

[242] N. Nykvist. The amounts of plant nutrients in stems of tropical rainforests. a literature review. In *Proceedings of International Symposium on Harvesting and Silviculture for Sustainable Forestry in the Tropics*, Kuala Lumpur, Oct 1992.

[243] J.S. Oguntoyinbo. Reflection coefficient of natural vegetation, crops and urban surfaces in Nigeria. *Quarterly Journal of the Royal Meteorological Society*, 96:430–441, 1970.

[244] C.L. O'Loughlin, L.K. Rowe, and A.J. Pearce. Sediment yield and water quality responses to clearfelling of evergreen mixed forests in western New Zealand. *International Association of Hydrological Sciences Publication*, 130:285–292, 1980.

[245] E.M. O'Loughlin, D.L. Short, and W.R. Dawes. Modelling the hydrological response of catchments to land use change. In *Hydrology and Water Resources Symposium*, number 19 in National Conference Publication, pages 335–340, Christchurch, Nov 1989. IE Aust.

[246] S.R. Olsen and L.E. Sommers. Phosphorus. In A.L. Page, D.E. Baker, and D.R. Keeney, editors, *Methods of Soil Analysis: Part 2.*, 9, chapter 24, pages 403–430. American Society of Agronomy Inc. and Soil Science Society of America Inc., madison, Wisconsin, USA, 2 edition, 1982.

[247] H.J.W.Y. Opdam. Evapotranspiration and rainfall interception for a 16-year-old *Pinus caribaea* plantation near Koromani, SW Viti Levu, Fiji. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit van Amsterdam, The Netherlands, 1993.

[248] J. Pardè. Forest biomass. *Forestry Abstracts*, pages 343–362, 1980.

[249] G.G. Parker. Throughfall and stemflow in the forest nutrient cycle. *Advances in Ecological Research*, 13:57–133, 1983.

[250] G.G. Parker. *The Effect of Disturbance on Water and Solute Budgets of Hillslope Tropical Rainforest in Northeastern Costa Rica.* PhD dissertation, University of Georgia, Athens, Georgia, Aug 1985.

[251] J.A. Parkinson and S.E. Allen. *Communications in Soil Science and Plant Analysis*, 6(1):1–11, 1975.

[252] A.J. Pearce and A.D. Griffiths. Effects of selective logging on physical water quality in small streams, Okarito forest. *Journal of Hydrology (New zealand)*, 19:60–67, 1980.

[253] A.J. Pearce and L.S. Hamilton. Water and soil conservation guidelines for land-use planning. Technical report, Environmental & Policy Institute, Honolulu, Hawaii, 1986. Summary of Seminar-Workshop on Watershed Land-Use Planning, May, 1985, Gympie.

[254] A.J. Pearce, C.L. O'Loughlin, and K. Rowe, L. Hydrologic regime of small undisturbed beech forest catchments, North Westland. *Soil and Plant Water Symposium*, pages 150–158, 1976.

[255] A.J. Pearce and L.K. Rowe. Rainfall interception in a multi-storied, evergreen mixed forest: Estimates using Gash's analytical model. *Journal of Hydrology*, 49:341–353, 1981.

[256] A.J. Pearce, L.K. Rowe, and J.B. Stewart. Nighttime, wet canopy evaporation rates and the water balance of an evergreen mixed forest. *Water Resources Research*, 16:955–959, 1980.

[257] A.J. Pearce, M.K. Stewart, and M.G. Sklash. Storm runoff generation in humid headwater catchments 1. where does the water come from? *Water Resources Research*, 22:1263–1272, 1986.

[258] H.L. Penman. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society*, 193:120–146, 1948. Series A.

[259] H.L. Penman. Evaporation: An introductory survey. *Netherlands Journal of Agricultural Science*, 4:9–29, 1956.

[260] H.L. Penman. Vegetation and hydrology. Technical communication 53, Commonwealth Agricultural Bureaux, Farnham Royal, Bucks, UK, 1963.

[261] L.L. Pierce and S.W. Running. Rapid estimation of coniferous forest leaf area index using a portable intergration radiometer. *Ecology*, 69:1762–1767, 1988.

[262] M.C. van der Plas and L.A. Bruijnzeel. Impact of mechanized selective logging of rainforest on topsoil infiltrability in the upper Segama area, Sabah, Malaysia. In J.S. Gladwell, editor, *Hydrology of Warm Humid Regions*, number 216 in IAHS Publication, pages 203–211, Institute of Hydrology, Wallingford, UK, Jul 1993. International Association of Hydrological Sciences, IAHS Press.

[263] J.L. Pleysier and A.S.R. Juo. A single-extraction method using silver-thiourea for measuring exchangeable cations and effective CEC in soils with variable charge. *Soil Science*, 129:205–211, 1980.

[264] R. Prasad. Tropical cyclone report 90/3: Tropical cyclone Rae. Information Sheet 3, Fiji Meteorological Service, Nadi, Fiji, Apr 1990.

[265] J. Proctor. Tropical forest litterfall. I. Problems of data comparison. In S.L. Sutton, T.C. Whitmore, and A.C. Chadwick, editors, *Tropical Rain Forest: Ecology and Management*, pages 267–273. Blackwell Scientific, 1983.

[266] J. Proctor. Nutrient cycling in primary and old secondary rain forests. *Applied Geography*, 7:135–152, 1987.

[267] S.J. Rance, D.M. Cameron, and E.R. Williams. Regressions to estimate fresh weight and dry matter production of young *Pinus caribaea* var. *hondurensis* under plantation conditions. *Malaysian Forester*, 45(2):209–216, 1982.

[268] T.T. Rawaqa. Navala land inspection report. Report of the Environmental Research Section, Fiji Pine Limited, Lautoka, Fiji, 1991.

[269] S.D. Reddy. Average wind speeds at Nadi Airport, Fiji. Information Sheet 40, Fiji Meteorological Service, Nadi, Fiji, May 1989. Revision 1.

[270] S.D. Reddy. Seasonal surface winds at Nadi Airport, Fiji. Information sheet 43, Fiji Meteorological Service, Nadi, Fiji, May 1989. Revision 1.

[271] S.D. Reddy. Extreme rainfalls at Nadi Airport, Fiji. Information sheet 52, Fiji Meteorological Service, Nadi, Fiji, Jun 1989. Revision 1.

[272] S.D. Reddy. Ambient air temperatures in Fiji. Information sheet 11, Fiji Meteorological Service, Nadi, Fiji, Jun 1989. Revision 1.

[273] S.D. Reddy. Average duration of bright sunshine at Fiji stations. Information sheet 69, Fiji Meteorological Service, Nadi, Fiji, Jul 1989. Revision 1.

[274] L.P. van Reeuwijk. Procedures for soil analysis. Technical Paper 9, International Soil Reference and Information Centre, The Netherlands, 1987.

[275] B.N. Richards and D.I. Bevege. The productivity and nitrogen economy of artificial ecosystems comprising various combinations of perennial legumes and coniferous tree species. *Australian Journal of Botany*, 15:467–480, 1967.

[276] J.H. Richardson. Some implications of tropical forest replacement in Jamaica. *Zeitschrift für Geomorphologie Neue Folge*, 44:107–118, 1982. Supplement Band.

[277] T.B. Ridder, T.A. Buishand, H.F.R. Reijnders, M.J. 'T Hart, and J. Slanina. Effects of storage on the composition of main components in rainwater samples. *Atmospheric Environment*, 19:759–762, 1985.

[278] H. Riehl. *Climate and Weather in the Tropics*. Academic Press, 1979.

[279] M.R. Rietveld. A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine. *Agricultural Meteorology*, 19:243–252, 1978.

[280] A. Rijsdijk and L.A. Bruijnzeel. Erosion, sediment yield and landuse patterns in the upper Konto watershed, East Java, Indonesia. Communication 18, Konto River Project, Malang, Indonesia, 1991. Volume 3.

[281] E.A. Ripley and R.E. Redman. Grassland. In J.L. Monteith, editor, *Vegetation and the Atmosphere Volume 2. Case Studies*, pages 349–398. Academic Press, London, 1976.

[282] J. Roberts, O.M.R. Cabral, and L.F. de Aguiar. Stomatal and boundary layer conductances in an Amazonian terra firme rain forest. *Journal of Applied Ecology*, 27:336–353, 1990.

[283] G.P. Robertson. Nitrification and denitrification in humid tropical ecosystems: Potential controls on nitrogen retention. In J. Proctor, editor, *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*, pages 55–69. Blackwell Scientific Publications, London, 1989.

[284] S.M. Robinson. Computing wind profile parameters. *Journal of Atmospheric Sciences*, 19:189–190, 1962.

[285] P. Rodda. Geology of Fiji. In A.J. Stevenson, R.H. Herzer, and P.F Ballance, editors, *Contributions to the Marine and On-land Geology and Resources of the Tonga-Lau-Fiji Region*, Technical Bulletin. South Pacific Applied Geoscience Commission (SOPAC), Suva, Fiji, 1989. in press.

[286] P. Rodda and R.B. Band. *Geology of Viti Levu.* Geological Survey of Fiji, Suva, Fiji, 1966. Map G.S. No. 432.

[287] W.F. Rogers. A practical model for linear and nonlinear runoff. *Journal of Hydrology*, 46:51–78, 1980.

[288] T.L. Rogerson. Throughfall in pole-sized loblolly pine as affected by stand density. In W.E. Sopper and H.W. Lull, editors, *International Symposium on Forest Hydrology*, pages 187–190. Pergamon Press, Oxford, UK, 1967.

[289] J. Ross. Radiative transfer in plant communities. In J.L. Monteith, editor, *Vegetation and the Atmosphere Volume 1. Principles*, chapter 2, pages 13–55. Academic Press, London, 1975.

[290] L.K. Rowe. Rainfall interception by an evergreen Beech forest, Nelson, New Zealand. *Journal of Hydrology*, 66:143–158, 1983.

[291] P.R. Rowntree. Estimates of the sensitivity of climate to vegetation changes using the Penman-Monteith equation. Climate Research Technical Note 1, Hadley Centre for Climate Prediction and Research, 1990.

[292] C.E. Russell. *Nutrient Cycling and Productivity of Native and Plantation Forests at Jari Forestal, Parà, Brazil.* PhD dissertation, University of Georgia, Athens, Georgia, Aug 1983.

[293] A.J. Rutter. An analysis of evaporation from a stand of Scots pine. In W.E. Sopper and H.W. Lull, editors, *International Symposium on Forest Hydrology*, pages 403–417. Pergamon Press, Oxford, UK, 1967.

[294] A.J. Rutter. The hydrological cycle in vegetation. In J.L. Monteith, editor, *Vegetation and the Atmosphere Volume 1. Principles*, chapter 4, pages 111–154. Academic Press, London, 1975.

[295] A.J. Rutter, K.A. Kershaw, P.C. Robbins, and A.J. Morton. A predictive model of rainfall interception in forests. I. derivation of the model from observations in a plantation of Corsican pine. *Agricultural Meteorology*, 9:367–384, 1971.

[296] A.J. Rutter, A.J. Morton, and P.C. Robbins. A predictive model of rainfall interception in forests. II. Generalization of the model and comparison with observations in some coniferous and hardwoods stands. *Journal of Applied Ecology*, 12:367–380, 1975.

[297] L.A. Salivia. *Historia de los Temporales de Puerto Rico y las Antillas, 1492–1970.* Editorial Edil, Inc., University of Puerto Rico, Rió Piedras, Puerto Rico, 1972.

[298] P.A. Sanchez. *Properties and Management of Soils in the Tropics.* J. Wiley and Sons, New York, 1976.

[299] F.N. Scatena and M.C. Larsen. Physical aspects of hurricane Hugo in Puerto Rico. *Biotropica*, 23(4):317–323, Dec 1991. Special Issue, Part A.

[300] F.N. Scatena, W. Silver, T. Siccama, A. Johnson, and M.J. Sánchez. Biomass and nutrient content of the Bisley experimental watersheds, Luquillo experimental forest, Puerto Rico, before and after hurricane Hugo. *Biotropica*, 25(1):15–27, 1993.

[301] J. Schellekens. Manual pages for HYD-TOOLS. Internal report, Institute of Earth Sciences, Vrije Universiteit van Amsterdam, 1991.

[302] J. Schellekens. Water and nutrient balance of the Oleolega catchment in the undisturbed state and its rainfall-runoff response. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit van Amsterdam, The Netherlands, 1992.

[303] J.P. Schulz. *Ecological Studies on Rain Forest in Northern Suriname*. North-Holland Publishing Company, 1960.

[304] R.E. Schulze and W.J. George. A dynamic, process-based, user-oriented model of forest effects on water yield. *Hydrological Processes*, 1:293–307, 1987.

[305] J. Shukla, C Nobre, and P. Sellers. Amazonian deforestation and climate change. *Science*, 247:1322–1325, 1990.

[306] W.J. Shuttleworth. Evaporation from Amazonian rain forest. *Philosophical Transactions of the Royal Society*, 223:321–346, 1988. Series B.

[307] W.J. Shuttleworth. Micrometeorology of temperate and tropical forest. *Philosophical Transactions of the Royal Society*, 324:299–334, 1989. Series B.

[308] W.J. Shuttleworth, J.H.C. Gash, C.R. Lloyd, C.J. Moore, A. de O. Marques-Filho, G. Fisch, V. de Paula Silva Filho, M. de Nazaré Góes Ribeiro, L.B. Molion, L.D. de Abreu Sá, J.C.A. Nobre, O.M.R. Cabral, S.R. Patel, and J.C. de Moraes. Eddy correlation measurements of energy partition for Amazonian forest. *Quarterly Journal of the Royal Meteorological Society*, 110:1143–1162, 1984.

[309] M.M. Singh. Average hourly sunshine duration at selected Fiji stations. Technical Note 17, Fiji Meteorological Service, Nadi Airport, 1983.

[310] M.G. Sklash, M.K. Stewart, and A.J. Pearce. Storm runoff generation in humid headwater catchments 2. A case study of hillslope and low-order stream response. *Water Resources Research*, 22:1273–1282, 1986.

[311] R.E. Smith and D.F. Scott. The effects of afforestation on low flows in various regions of South Africa. *Water South Africa*, 18(3):185–194, 1992.

[312] M.R. Spiegel. *Theory and Problems of Statistics*. McGraw-Hill Book Company, London, UK, 1972. Schaum's Outline Series.

[313] W.P. Stakman. Measuring soil moisture. In *I.L.R.I. Publication no. 16. Volume III.*, pages 221–251. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 1973.

[314] G. Stanhill. A simple instrument for field measurement of turbulent diffusion flux. *Journal of Applied Meteorology*, 8:509–513, 1969.

[315] N. Stark. The nutrient content of plants and soils from Brazil and Surinam. *Biotropica*, 2(1):51–60, 1970.

[316] L. Steubing and A. Fangmeier. *Pflanzen Ökologisches Praktikum*. Verlag Eugen Ulmer, Stuttgart, 1992.

[317] P.A. Steudler, J.M. Melillo, R.D. Bowden, and M.S. Castro. The effects of natural and human disturbances on soil nitrogen dynamics and trace gas fluxes in a Puerto Rican wet forest. *Biotropica*, 23(4):356–363, Dec 1991. Special Issue, Part A.

[318] J.B. Stewart. Evaporation from the wet canopy of a pine forest. *Water Resources Research*, 13(3):915–921, 1977.

[319] J.B. Stewart and A.S. Thom. Energy budgets in pine forests. *Quarterly Journal of the Royal Meteorological Society*, 99:154–170, 1973.

[320] J.J. Stoorvogel. *Gross Inputs and Outputs of Nutrients in Undisturbed Forest, Taï Area, Côte d'Ivoire*, volume 5 of *Tropenbos Series*. The Tropenbos Foundation, Wageningen, The Netherlands, 1993.

[321] P. Stromgaard. The immediate effect of burning and ash fertilization. *Plant and Soil*, 80:307–320, 1984.

[322] P.J. Stuijfzand. *Hydrochemistry and Hydrology of the Coastal Dune Area of the Western Netherlands*. PhD dissertation, Vrije Universiteit, Amsterdam, 1993.

[323] W. Stumm and J.J. Morgan. *Aquatic Chemistry.* John Wiley & Sons, Inc., New York, 2 edition, 1981.

[324] M. Sugita. Evaporation from a pine forest. Environmental Research Center Papers 10, The University of Tsukuba, Japan, 1987.

[325] B.A. Sutjahjo. Produksi dan akumulasi seresah pada tegakan *Pinus merkusii* Jungh. *et* de Vriese di BKPH Lawa Utara, KPH, Surakarta. Master's thesis, Faculty of Forestry, Gadjah Mada University, Yogyakarta, Indonesia, 1975. Skripsi.

[326] W.T. Swank. Stream chemistry in response to discharge. In W.T. Swank and D.A. Jr. Crossley, editors, *Forest Hydrology and Ecology and Ecology at Coweeta*, number 66 in Ecological Studies, chapter 25, pages 339–357. Springer-Verlag, New York, 1987.

[327] W.T. Swank and H.T. Schroeder. Comparison of three methods of estimating surface area and biomass for a forest of young eastern white pine. *Forest Science*, 20(1):91–100, 1974.

[328] W.T. Swank and J.B. Waide. Characterization of baseline precipitation and stream chemistry and nutrient budgets for control watersheds. In W.T. Swank and D.A. Jr. Crossley, editors, *Forest Hydrology and Ecology and Ecology at Coweeta*, number 66 in Ecological Studies, chapter 4, pages 57–79. Springer-Verlag, New York, 1987.

[329] M.J. Swift and J.M. Anderson. Decomposition. In H. Lieth and M.J.A. Werger, editors, *Tropical Rain Forest Ecosystems – Biogeographical and Ecological Studies*, Ecosystems of the World 14B, pages 547–569. Elsevier, Amsterdam, The Netherlands, 1989.

[330] M.J. Swift, O.W. Heal, and J.M. Anderson. *Decomposition in Terrestrial Ecosystems.* Blackwell Scientific Publications, London, 1979.

[331] B.F. Swindel, C.J. Lassiter, and H. Riekerk. Effects of different harvesting and site preparation operations on the peak flows of streams in *Pinus elliottii* flatwoods forests. *Forest Ecology and Management*, 5:77–86, 1983.

[332] B.F. Swindel, C.J. Lassiter, and H. Riekerk. Effects of clearcutting and site preparation operations on water yields from Slash pine forests. *Forest Ecology and Management*, 5:101–113, 1983.

[333] B.F. Swindel, C.J. Lassiter, and H. Riekerk. Effects of clearcutting and site preparation operations on stormflow volumes of streams in *Pinus elliottii* flatwoods forests. *Forest Ecology and Management*, 5:245–253, 1983.

[334] G. Szeicz, G. Endrodi, and S. Taichman. Aerodynamic and surface factors in evaporation. *Water Resources Research*, 5:380–394, 1969.

[335] K. Tannai and S. Hattori. Apportionment of evapotranspiration of a deciduous broad-leaved forest. In H.J. Bolle, R.A. Feddes, and J.D. Kalma, editors, *Exchange Processes at the land surface for a Range of Space and Time Scales*, number 212 in IAHS Publication. International Association of Hydrological Sciences, IAHS Press, Jul 1993.

[336] The Fiji Times. The timber industry. The Fiji Times of April 24, 1990. Supplement.

[337] A.S. Thom. Momentum, mass and heat exchange of plant communities. In J.L. Monteith, editor, *Vegetation and the Atmosphere. Volume 1. Principles*, chapter 3, pages 57–109. Academic Press, London, 1975.

[338] S.R. Tiedemann, C.E. Conrad, J.H. Dieterich, J.W. Hornbeck, W.F. Megahan, L.A. Viereck, and D.E. Wade. Effects of fire on water: A state of knowledge review. Forest service general technical report wo-10, USDA, 1979.

[339] J.E. Tillman. The indirect determination of stability, heat and momentum fluxes in the atmosphere boundary layer from simple scalar variables during dry unstable conditions. *Journal of Applied Meteorology*, 11:783–792, 1972.

[340] J.C. Tosin. Influence of *Pinus elliotii*, *Auracaria augustifolia* and natural forest on the activity of soil microflora. Master's thesis, Parana Federal University, Parana, Brazil, 1977.

[341] J. Turner and M.J. Lambert. Nutrition and nutritional relationships of *Pinus radiata*. *Annual Reviews of Ecological Systems*, 17:325–350, 1986.

[342] N.D. Turvey. Nutrient cycling under tropical rain forest in Central Papua. Occasional Paper 10, Department of Geography, University of Papua New Guinea, Port Moresby, 1974.

[343] N.D. Turvey. Water quality in a tropical rain forest catchment. *Journal of Hydrology*, 27:111–125, 1975.

[344] I.T. Twyford and A.C.S. Wright. *The Soil Resources of the Fiji Islands*. Government Printer, Suva, Fiji, 1965. 2 Volumes.

[345] C. Uhl, R. Buschbacher, and E.A.S. Serrao. Abandoned pastures in eastern Amazonia. I. Patterns of plant succession. *Journal of Ecology*, 76:663–681, 1988.

[346] C. Uhl and C.F. Jordan. Succession and nutrient dynamics following forest cutting and burning in Amazonia. *Ecology*, 65(5):1476–1490, 1984.

[347] C. Uhl, C.F. Jordan, K. Clark, H. Clark, and R. Herrera. Ecosystem recovery in Amazon caatinga forest after cutting, cutting and burning, and bulldozer clearing treatments. *Oikos*, 38:313–320, 1982.

[348] USDA Soil Survey Staff. Soil taxonomy. Agriculture Handbook 436, U.S.D.A., Washington D.C., 1975.

[349] J. *et al.* Viessman. *Introduction to Hydrology*. Harper & Row Publishers, 1977. Second Edition.

[350] P.M. Vitousek. Nutrient cycling and nutrient use efficiency. *American Naturalist*, 119:553–572, 1982.

[351] P.M. Vitousek. Litterfall, nutrient cycling and nutrient limitation in tropical forests. *Ecology*, 65(1):285–298, 1984.

[352] P.M. Vitousek and R.L. Sanford Jr. Nutrient cycling in moist tropical forest. *Annual Reviews of Ecological Systems*, 17:137–167, 1986.

[353] J.M. Vose and W.T. Swank. Assessing seasonal leaf area dynamics and vertical leaf area distribution in eastern white pine *Pinus strobus* L. with a portable light meter. *Tree Physiology*, 7:125–134, 1990.

[354] H.F. Vugts, M.J. Waterloo, F.J. Beekman, K.F.A. Frumau, and L.A. Bruijnzeel. The temperature variance method: a powerful tool in the estimation of actual evaporation rates. In J.S. Gladwell, editor, *Hydrology of Warm Humid Regions*, number 216 in IAHS Publication, pages 251–260, Institute of Hydrology, Wallingford, UK, Jul 1993. International Association of Hydrological Sciences, IAHS Press.

[355] L.R. Walker. Tree damage and recovery from hurricane Hugo in Luquillo experimental forest, Puerto Rico. *Biotropica*, 23(4):379–385, Dec 1991. Special Issue, Part A.

[356] R.C. Ward. On the response to precipitation of headwater streams in humid areas. *Journal of Hydrology*, 74:171–189, 1984.

[357] R.C. Ward and M. Robinson. *Principles of Hydrology*. McGraw-Hill, Maidenhead, UK, 1990.

[358] R.H. Waring and W.H. Schlesinger. *Forest Ecosystems: Concepts and Management*. Academic Press, Orlando, Florida, 1985.

[359] M.J. Waterloo. A hydrological study of the mass elevation effect on Gunung Silam, a small coastal ultrabasic mountain in Sabah, East Malaysia. Master's thesis, Vrije Universiteit van Amsterdam, Amsterdam, The Netherlands, 1989.

[360] R. van der Weert. Influence of mechanical forest clearing on soil conditions and the resulting effects on root growth. *Tropical Agriculture (Trinidad)*, 51:325–331, 1974.

[361] R. van der Weert and K.J. Lenselink. The influence of mechanical clearing of forest on some physical and chemical soil properties. *Surinaamse Landbouw*, 20(3):2–14, 1972.

[362] E.P. Weijers and H.F. Vugts. An observational study on precipitation chemistry data as a function of surface wind direction. *Water, Air, and Soil Pollution*, 52:115–132, 1990.

[363] B. van Well. Determination of evapotranspiration for a mature *Pinus caribaea* plantation forest. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit Amsterdam, The Netherlands, 1993.

[364] B. van Well. Effects of clearing and burning on water yield and nutrient losses of the Oleolega catchment, Viti Levu, Fiji. Master's thesis, Faculty of Earth Sciences, Vrije Universiteit Amsterdam, The Netherlands, 1993.

[365] S.R. Wellings and J.P. Bell. Movement of water and nitrate in unsaturated chalk. *Journal of Hydrology*, 48:119–136, 1980.

[366] E.J. White and F. Turner. A method of estimating nutrient income in a catch of airborne particles by a woodland canopy. *Journal of Applied Ecology*, 7:441–446, 1970.

[367] H.G. Whitehead and J.H. Feth. Chemical composition of rain, dry fallout, and bulk precipitation at Menlo Park, California, 1957–1959. *Journal of Geophysical Research*, 69:3319–3333, 1964.

[368] T.C. Whitmore. *Introduction to Tropical Rain Forests*. Clarendon Press, Oxford, UK, 1990.

[369] D.B. van Wijk. Die invloed van bebossing met *Pinus radiata* op die totale jaarlikse afvoer van die Jonkershoek strome. Master's thesis, University of Stellenbosch, Stellenbosch, South Africa, 1977. Unpublished.

[370] G.M. Will. Decomposition of *pinus radiata* litter on the forest floor. Part 1. changes in the dry matter nutrient content. *New Zealand Journal of Science*, 10:1030–1044, 1967.

[371] M. Witkamp and J.S. Olson. Breakdown of confined and nonconfined oak litter. *Oikos*, 14(2), 1963.

[372] WMO. Technical regulations 49, World Meteorological Organisation, 1984. Appendix A. 1-Ap-A-3.

[373] W.W. Wood. A technique using porous cups for water sampling at any depths in the saturated zone. *Water Resources Research*, 9:486–488, 1973.

[374] I.R. Wright, J.H.C. Gash, H.R. da Rocha, W.J. Shuttleworth, C.A. Nobre, G.T. Maitelli, C.A.G.P. Zamparoni, and P.R.A. Carvalho. Dry season micrometeorology of Central Amazonian ranchland. *Quarterly Journal of the Royal Meteorological Society*, 1992. Submitted.

[375] J.C. Wyngaard and O.R. Cote. The budgets of turbulent kinetic energy and temperature variance in the atmospheric surface layer. *Journal of Atmospheric Sciences*, 28:190–201, 1971.

[376] K.T. Yabaki. Annual report of the Fiji Pine Commission. Annual report, Fiji Pine Commission, P.O. Box 521, Lautoka, Fiji, 1989.

[377] K.T. Yabaki. Annual report of the Fiji Pine Limited. Annual report, Fiji Pine Ltd., P.O. Box 521, Lautoka, Fiji, 1991.

[378] D.M. Zall, D. Fischer, and M.D. Garner. Photometric determination of chlorides in water. *Analytical Chemistry*, 28:1665, 1956.

[379] C.F. Zimmermann, M.T. Price, and J.R. Montgomery. A comparison of ceramic and teflon *in situ* samplers for nutrient pore water determinations. *Estuarine, Coastal and Marine Sciences*, 6:93–97, 1978.

[380] P.J. Zinke. Forest interception studies in the United States. In W.E. Sopper and H.W. Lull, editors, *International Symposium on Forest Hydrology*, pages 137–161. Pergamon Press, Oxford, UK, 1967.

[381] Zulkifli Yusop and Abdul Rahim. Logging and forest conversion: Can we minimize their impacts on water resources. Paper presented at ASEAN Seminar on 'Land Use Decisions and Policies: Will Tropical Forest Survive their Impact', Penang, Malaysia, Oct 1991.

Chapter 22

List of Symbols and Formulas

22.1 Symbols

The following list gives a short description of the symbols used throughout this book with their units.

Symbol	Description and unit
A	Available energy for partitioning over H and λE [W m^{-2}]
A_f	Forest age [years]
API	Antecedent precipitation index [mm]
α	Albedo for short-wave radiation
α_{par}	Albedo for photosynthetic active radiation
β	Bowen ratio
c_p	Specific heat of air at constant pressure [J kg^{-1} K^{-1}]
Γ	Adiabatic temperature lapse rate [K m^{-1}]
γ	Psychrometric constant [mbar K^{-1}]
d	Zero plane displacement length [m]
D	Drainage [mm]
D_a	Horizontal flux divergence [W m^{-2}]
D_{lf}	Drainage from litter layer [mm]
$Dbhob$	Diameter at breast height over bark [m]
Dob	Diameter over bark [m]
Dub	Diameter under bark [m]
Δ	Change of the saturation vapour pressure with temperature [mbar K^{-1}]
$\bar{E}$	Average evaporation from a wet canopy [mm h^{-1}]
ET	Evapotranspiration [mm t^{-1}]
E_i	Interception loss from canopy [mm]
E_l	Evaporation rate from litter layer [mm h^{-1}]
E_{il}	Interception loss from litter layer [mm]
E_{it}	Interception loss from trunks [mm]
E_0	Penman open water evaporation [mm]
E_t	Transpiration rate [mm day^{-1}, mm year^{-1}
ET_{sm}	Evapotranspiration obtained from soil moisture depletion [mm]
ET_{pm}	Evapotranspiration rate obtained for Penman-Monteith mode [mm]

e	Water vapour pressure in air [mbar]
e_s	Saturation vapour pressure of air [mbar]
G	Flux density of heat into the soil [W m^{-2}]
ΔG	Change in groundwater storage [mm]
g	Gravitational acceleration [m s−2]
Γ	Adiabatic lapse rate [K m^{-1}]
γ	Psychrometric constant [mbar K^{-1}]
H	Sensible heat flux [W m^{-2}]
H	Water level or pressure [cm H_2O]
h	Mean vegetation height [m]
J_h	Sensible heat storage within the forest [W m^{-2}]
J_w	Latent heat storage within the forest [W m^{-2}]
J_{veg}	Energy storage in the biomass [W m^{-2}]
K_H	Eddy diffusivity for heat [m^2 s^{-1}]
K_M	Eddy diffusivity for momentum [m^2 s^{-1}]
K_E	Eddy diffusivity for water vapour [m^2 s^{-1}]
K_L	Litter turnover rate [year^{-1}]
k	Von Karman's constant, set to 0.4
κ	Light extinction coefficient
L	Leakage losses from catchment [mm]
LAI	Leaf area index [m^2 m^{-2}]
λ	Latent heat of vapourization of water [J kg^{-1}]
λE	Latent heat flux [W m^{-2}]
MC_l	Moisture content of the litter layer [mm]
M_l	Litter layer mass [kg ha^{-1}]
M_{veg}	Fresh forest biomass [kg m^{-2}]
n	Sample size
N	Maximum daily sunshine duration [h]
n	Actual daily sunshine duration [h]
P	Rainfall total [mm]
P_a	Mean areal precipitation [mm]
P_g	Above canopy rainfall [mm]
P'_g	Amount of rainfall necessary to fill the canopy storage [mm]
P_{veg}	Energy flux into biochemical storage [W m^{-2}]
p	Free throughfall coefficient
p_t	Fraction of rainfall diverted to tree trunks
Q	Below canopy photosynthetic active radiation [μmol m^{-2} s^{-1}]
Q_s	Incoming photosynthetic active radiation [μmol m^{-2} s^{-1}]
Q	Streamflow output [mm; l s^{-1}; mm h^{-1}]
Q_b	Baseflow [mm; l s^{-1}; mm h^{-1}]
Q_p	Peak discharge [mm; l s^{-1}; mm h^{-1}]
Q_s	Stormflow [mm; l s^{-1}; mm h^{-1}]
q	Specific humidity of air [kg m^{-3}]
$R_s \downarrow$	Incoming short-wave radiation [W m^{-2}]
$R_s \uparrow$	Reflected short-wave radiation [W m^{-2}]
$\bar{R}$	Average rainfall rate on a wet canopy
R_{ET}	Incoming short-wave radiation at the top of the atmosphere [W m^{-2}]
RH	Relative humidity [%]
R_n	Net radiation [W m^{-2}]
R_{lw}	Reflected shortwave radiation [W m^{-2}]
r_a	Aerodynamic resistance [s m^{-1}]
r_s	Surface or canopy resistance [s m^{-1}]
r_{st}	Stomatal resistance [s m^{-1}]
ρ	Density of air [kg m^{-3}]
S	Canopy storage capacity [mm]
Sf	Stemflow [mm]
S_l	Litter layer moisture storage capacity [mm]

S_t	Storage capacity of tree trunks [mm]
SMD	Soil moisture deficit [mm]
SV	Stormflow volume [mm]
ΔS	Change in soil moisture storage [mm]
T	Temperature [°C; K]
Tf	Throughfall [mm]
t	Time [s; h; day; year]
θ	Volumetric soil moisture content [m^3 m^{-3}]
$u(z)$	Wind speed at height z above the soil surface [m s^{-1}]
u_*	Friction velocity [m s^{-1}]
VPD	Vapour pressure deficit [mbar]
z	Height above the surface [m]
z_0	Aerodynamic roughness length [m]

22.2 Micrometeorological Formulas

22.2.1 Formulas for general use

In this section the formulas used for the calculation of micrometeorological 'constants', as well as those used to calculate parameters dependent on temperature and relative humidity will be presented. The following formula (WMO, 1984a) was used to calculate the saturated vapour pressure (e_{sat}, in mbar) from the temperature (T, in K):

$$\begin{aligned} e_{sat} &= 10^{10.79574\left(1-\frac{T_0}{T}\right)-5.028\log\left(\frac{T}{T_0}\right)+1.50475\cdot 10^{-4}\left(1-10^{-8.2969\left(\frac{T}{T_0}-1\right)}\right)} \\ &\quad * 10^{0.42873\cdot 10^{-3}\left(10^{4.76955\left(1-\frac{T_0}{T}\right)}-1\right)+0.78614} \end{aligned}$$

where T_0 is 273.15 K.

The actual vapour pressure e can be obtained from e_{sat} and the relative humidity (RH, in %):

$$e = \frac{RH}{100}\cdot e_{sat}$$

The specific humidity of the air (q, in kg m^{-3}) can be approximated by:

$$q = 0.622\cdot\frac{e}{p-0.378e}$$

where p was set at 998 mbar.

The slope of the saturated vapour pressure curve (Δ, in mbar K^{-1}) is obtained by differentating the equation used to calculate e_{sat} with respect to T (WMO, 1984a):

$$\begin{aligned} \Delta &= \frac{de_{sat}}{dT} \\ &= e_{sat}\cdot[\frac{10.79574T_0}{0.4343T^2} - 5.028\frac{1}{T} \\ &\quad + 1.50475\cdot 10^{-4}\frac{8.2969}{0.4343^2 T_0}\cdot 10^{8.2969\left(1-\frac{T}{T_0}\right)} \\ &\quad +0.42873\cdot 10^{-3}\frac{4.76955T_0}{0.4343^2T^2}\cdot 10^{4.76955\left(1-\frac{T_0}{T}\right)}] \end{aligned}$$

The latent heat of vapourization (λ, in J kg^{-1}) is dependent on the temperature (T, in K) and was calculated as follows (Bringfelt, 1986):

$$\lambda = 4185.5\cdot(751.78-0.5655T)$$

The specific heat of air (c_p, in J kg^{-1} K^{-1}) from e, where the atmospheric pressure p was assumed constant at 998 mbar:

$$c_p = 0.24 \cdot 4185.5 \left(1 + 0.8\frac{0.622e}{p-e}\right)$$

The density of the air (ρ, in kg m^{-3}) fluctuates with the temperature (T, in K), vapour pressure (e, in mbar) and pressure (p, set at 998 mbar) of the air and can be calculated from the following expression:

$$\rho = 1.201\frac{290 \cdot (p - 0.378e)}{1000T}$$

The psychrometric constant was calculated as (Bringfelt, 1986):

$$\gamma = \frac{c_p \cdot p}{0.622 \cdot \lambda}$$

22.2.2 Penman Open Water Evaporation

The Penman open water evaporation (E_0, in mm day^{-1}) may be written as (Penman, 1956, 1963):

$$E_0 = \frac{\Delta \cdot R_n + \gamma \cdot E_a}{\Delta + \gamma} \tag{22.1}$$

where R_n represents the net radiation for an open water surface and E_a represents the aerodynamic evaporation. The daily input of net radiation (mm day^{-1}) for an open water surface is given by:

$$R_n = R_s \downarrow (1 - \alpha) - R_{ln} \tag{22.2}$$

where R_g is the incoming short-wave radiation (mm day^{-1}), α the albedo of open water (0.05) and R_{ln} the net-longwave radiation (mm day^{-1}), which can be obtained as follows:

$$R_{ln} = \frac{86400\sigma T^4(0.56 - 0.248\sqrt{e}) \cdot (0.1 + 0.9n/N)}{\lambda} \tag{22.3}$$

where σ is the Stefan-Boltzmann constant ($5.670 \cdot 10^{-8}$ W m^{-2} K^{-4}), T is the daily average air temperature (K), e is the average daily water vapour pressure of the air (kPa), n is the duration of bright sunshine (h), N is the maximum possible sunshine duration (h). The aerodynamic term (mm day^{-1}) is a function of the wind speed and vapour pressure deficit (Calder, 1990):

$$E_a = 2.6(1 + 0.537u) \cdot (e_{sat} - e) \tag{22.4}$$

where u is the wind speed (m s^{-1}). Conventionally, all micrometeorological parameters should be measured at a height of 2 m above ground level.

Chapter 23

Oleolega Rock Sample Mineralogy

Seven rock samples were collected at various locations in the Oleolega catchment, and the mineralogy was optically determined from thin slides by Mr. H. Helmers at the Institute of Earth Sciences from the Free University of Amsterdam. The number of each of the rock samples described below corresponds with the sample location as shown in Figure 15.3. Most of the rock outcrops on the ridges in the catchment were strongly weathered and crumbled under pressure. Relatively fresh samples could only be collected in the stream valleys (boulders in the creek). However, the exact origin from these samples could not be traced.

Rock sample (1) collected *in situ* at the catchment outlet The rock consisted of fine grained plagioclase (microphanerite), clino-pyroxene ortho-pyroxene (augite) and and evenly distributed ore mineral (ilmenite or titanite). The pyroxene seemed to be transformed to olivine. Small amounts of calcite and chlorite of secundary origin were present. Some of the chlorite was of late magmatic origin, whereas some was formed by transformation of primary minerals. Flow structure were not present. The sample could be classified as a basalt (diabase).

Rock sample (2) collected *in situ* at the catchment outlet The rock consisted of fine grained plagioclase (Anorthite 38) with hornblende, hyperstene, magnetite and pyrite as accessory minerals. The ore was not regularly distributed. The rock showed signs of metamorphosis with some of the hyperstene being transformed to anthophyllite. The mineral association indicated high temperature transformation. The rock may have been part of a lava flow and was classified as an andesite. The chemical composition of the rock has been given in Table 4.5 (Rock1).

Rock sample 4 The rock consisted of plagioclase phenocrists, clay minerals and some secundary quartz, which were well distributed indicating a magmatic origin. There were many signs of hydrothermal secundary recrystallization, with most of the quartz being recristallized. The rock showed pseudomorphosis, with amphiboles and pyroxenes being replaced by clay minerals, possibly in a Mg rich solution, indicated by the presence of chlorite. Some opaque ore was present in the rock (Iron, pyrite). Features concentrated around air inclusions, and the matrix showed some of the original flow structures. The presence of secundary minerals made it difficult to classify the rock, but it may have been part of a trachite or dacite lava flow.

Rock sample 33 This rock sample was very similar in mineral content as rock sample 4. However, there were fewer phenocrists, and the plagioclase crystals were stretched. The flow structure was very vague. The sample could be classified as part of a dacite lava flow.

Rock sample 11, collected *in situ* This rock was similar to sample 4 and 33, but more weathered and transformed. Euhedric plagioclase and quartz formed clusters, which are indicative for flow conditions. Since the flow structures were less evident than in sample 4, the flow may have stopped during matrix cristallization. Spherolite of late magmatic origin was present, and some ore was observed surrounded by spherolite. The rock was classified as a dacite.

Rock sample 14a This rock, and sample 14b, were collected in the creek, and the exact origin (upstream of sample point 14) is therefore unknown. The matrix consisted of orthophyric plagioclase, and contained a large number of plagioclase phenokrists (40%), as well as some high temperature quartz (<5%), pyroxene, and some opaque ore minerals (pyrite). The rock had undergone low temperature metamorphosis and the pyroxene had been altered to carbonate and chlorite. The presence of phrenite indicated that the temperature had been lower than 400 °C, whereas the presence of a zeolite vein suggested transformation at a temperature below 200 °C. Some of the ore had been weathered to limonite. The rock was classified as a quartz-andesite lava and the chemical composition has been given in Table 4.5 (Rock2).

Rock sample 14b The matrix consisted of spherulites of felsophyric plagioclase, some quartz and traces of K-feldspar. The structure of the matrix suggested that the rock had cooled down rapidly after formation, preventing the forming of phenocrists, although some plagioclase phenocrists had formed. However, initial cooling had been slow as indicated by the presence of antiperthites (demixing of K-feldspar and plagioclase). Accessory minerals were cericite (fine grained muscovite), chlorite (altered pyroxene), titanite, and some ore minerals (pyrite). The rock was classified as a leuco-andesite (light colored) or dacite lava and the chemical composition has been given in Table 4.5 (Rock3).

On the basis of these samples two rock types could be identified in the catchment. Dacite lavas were found in the northern and middle part of the catchment, and these were grading into andesite and basalt lava flows in the southernmost part of the catchment.

Chapter 24

Capacitance Soil Moisture Probe

24.1 Use and Calibration Procedures

A capacitance soil moisture probe (type IH1, Didcot Instruments Company Ltd., Oxford, UK) was used to measure profiles of the volumetric soil moisture content (θ) at the grassland and forest sites.

The dielectric constant (ε) of a composite material is determined by the dielectric constants and proportions of its constituents. As ε of dry soil at frequencies below 1000 MHz is typically about 4 and that of water is about 80 (Dean *et al.* 1987) small changes in θ result in relatively large changes of ε. As such estimates of θ can be obtained from measured ε values using appropriate calibration curves.

The design and performance of a prototype of the capacitance probe have been discussed in detail by Dean *et al.* (1987) . The probe consists of a sensor linked to a hand held frequency reader by a fibre optic cable. The sensor measures ε of the soil with a temperature compensated, highly stable, electronic oscillator and the output is displayed by the frequency reader. A series of extension handles are used to lower the sensor into PVC access tubes. An access tube extension piece is placed on the access tube and a pin on top of this extension tube, which fits into holes placed at a 2 cm interval over the length of the extension handles, ensures that measurements are always made on the same depths in the access tubes and that the orientation of the sensor is always the same.

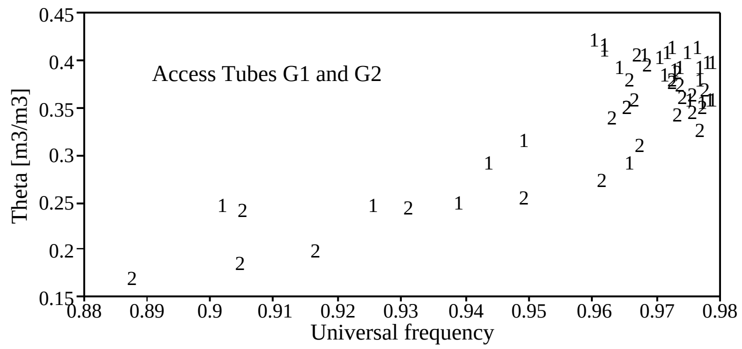
The probe is sensitive over a total vertical extent of 34 cm, independent of the medium, with 90% of the response coming from a region 8.5 cm above and below the centre of sensitivity (Dean *et al.* 1987). Bell *et al.* (1987) observed that the bulk of the response was derived from a 4–8 cm thick soil layer and that the influence of the surface–air interface extended down to a depth of about 20 cm. The penetration in the horizontal direction is rather small with 90% of the response comming from the soil within a radius of 13 cm of the centre of sensitivity of the probe (Dean *et al.*, 1987).

The frequency output of the probe is influenced by variations in temperature and these can therefore not be used directly for the calculation of θ. As such a universal frequency (UF) is calculated (Equation 24.1) from frequency readings taken in the soil (F_s) using the frequency measured in the access tube extension, which is read at the start and end of each measurement and represents the frequency measured in air (F_a), and that measured in an access tube fully submerged in water (F_w).

$$UF = \frac{F_a^{7.692} - F_s^{7.692}}{F_a^{7.692} - F_w^{7.692}} \tag{24.1}$$

For the probe sensor used in the present study F_a ranged from 17610–17640 kHz during the warm wet season and from 17640–17670 kHz during the cool dry season. F_w was measured on four occassions during both seasons and was 4430±4 kHz lower than the corresponding F_a (range 17618–17653 kHz).

The probe has a nonlinear response to changes in θ and is most sensitive at moisture volume fractions below 0.35 m^3 m^{-3} as shown in Figures 24.1 and 24.2 where plots of UF against θ are shown for all access tubes. The porosity of the soils in the Nabou Estate



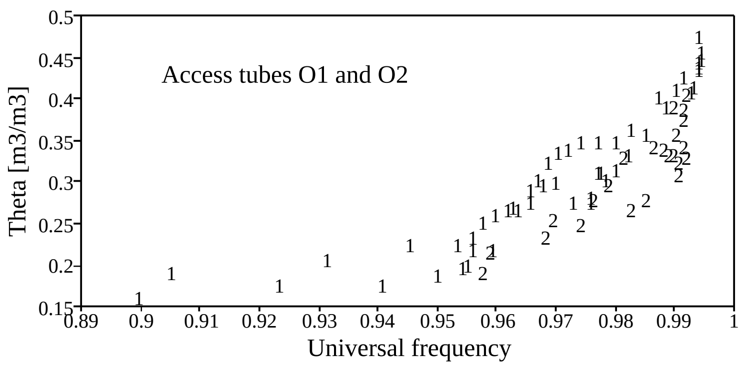


Figure 24.1: *Plots of θ (m^3 m^{-3}) against UF for access tubes in grassland (G1 and G2) and Oleolega drainage basin (O1 and O2). The data labels represent access tube numbers, samples collected above a depth of 10 cm were excluded as the UF was strongly influenced by the soil–air interface.*

was generally high (40–65%) due to the large proportions of fine grained weathering products (clay and silt), resulting in observed θ values up to 0.60 m^3 m^{-3} (Access tubes A3, B5). Furthermore the spatial variation in soil depth, stucture, texture and bulk density between and within the research sites was considerable and separate calibration curves were therefore needed for each access tube. The bulk density often increased considerable with depth in a soil profile and separate calibrations had to be made for the various soil layers. As the soil moisture probe is very sensitive to small variations in soil properties and θ it was not possible to calibrate the probe using samples collected in the vicinity of the access tube as is the normal procedure for the calibration of the neutron probe (Bell *et al.*, 1987). The capacitance probe was therefore calibrated on θ values obtained from soil samples removed during installation of the access tube. Soil samples were collected at 4 cm depth intervals over the length of each

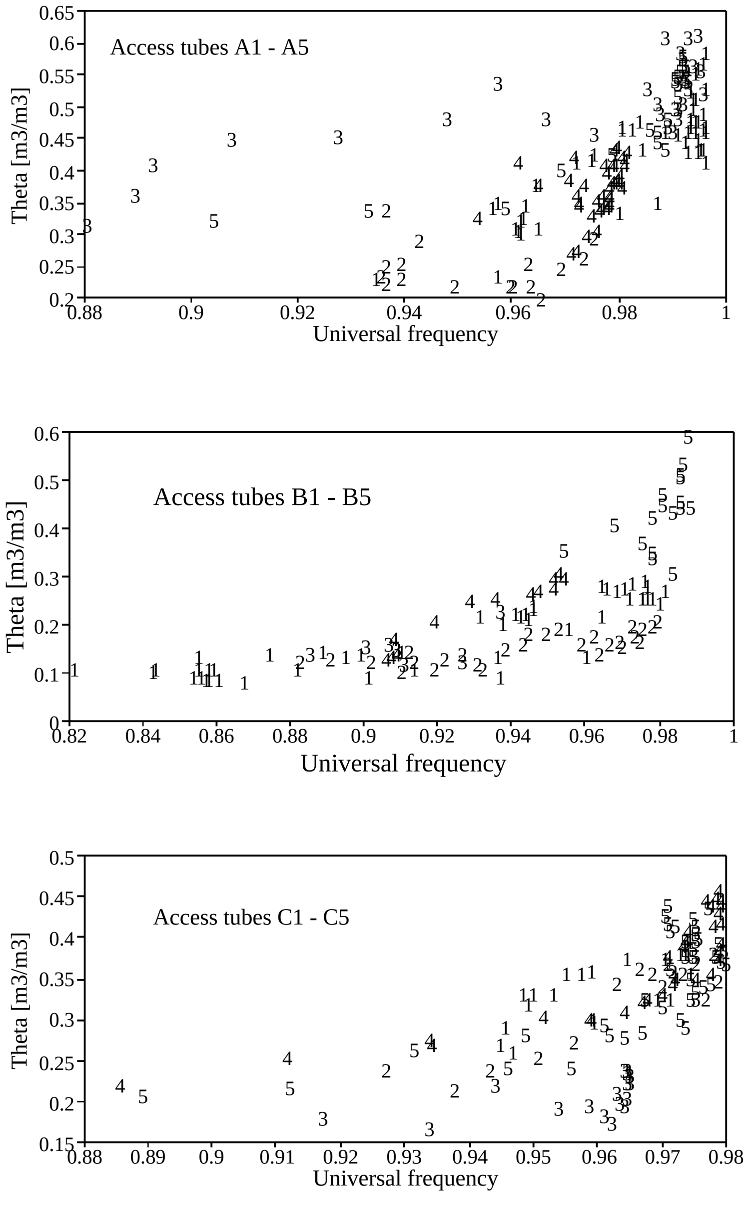


Figure 24.2: *Plots of θ (m^3 m^{-3}) against UF for access tubes in Tulasewa (A1–A5), Korokula (B1–B5) and Koromani forests (C1–C5). The data labels represent access tube numbers, samples collected above a depth of 10 cm were excluded as the UF was strongly influenced by the soil–air interface.*

access tube. As the volume of the soil removed at each interval was known (78.5 cm^3) θ and the bulk density could be calculated from the measured field and dry weights (105° C). Frequency readings corresponding with the observed θ values were obtained by lowering the probe sensor into the access tube immediately after installation. Readings were always taken over the length of the tube at 2 cm depth intervals. Instrumental drift during the measurements was determined by taking readings of F_a before and after measuring the profile. The instrumental drift was usually negligible as the measurement of a profile was usually completed within 3–5 minutes.

The calibration procedure given above is based on the assumption that the frequency output of the sensor responds mainly to the moisture status of the soil and that effects of variations in soil structure, texture and bulk density are negligible. Calibration becomes troublesome when either the variation of θ is small throughout the profile or when large contrasts exist between the characteristics (*e.g.* bulk density) of the soil layers. In the former case the relatively large scatter in the calibration data, caused by the small range of UF and θ, results in a poor fit of the regression line, whereas in the latter case the regression lines for the various horizons are based on few calibration points which may also limit the range of UF and *theta*. In both cases large uncertainties exist in the regression constants (*e.g.* slope of the regression line) as indicated by low coefficients of determination. However, there are several ways in which the calibrations may be improved. One way is to combine the data from several access tubes with soil layers having similar characteristics to extend the range of UF and θ. An alternative is to obtain additional calibration data by collecting soil samples within 10 cm of the access tubes immediately after frequency readings have been taken. This should be done at the end of the study as the access tubes cannot be used afterwards. When the foregoing is not possible the calibration of dry soil sections, of which the θ at saturation (porosity) is well known can be improved by the inclusion of a fictional calibration point assuming that $UF = 1.00$ at saturation.

During the present study additional calibration data were obtained for several access tubes using an auger to collect soil samples within 8 cm of the tubes at 10 cm depth intervals. The gravimetric moisture contents obtained from these samples were multiplied with the bulk densities corresponding with the sample depths as obtained from the samples collected at installation of the tubes.

Linear regression analysis was used to obtain expressions for the calculation of θ from UF. The regression models used for the calibrations were the linear model (Equation 24.2), the exponential model (Equation 24.3) and the reciprocal model (Equation 24.4).

$$\theta = a \cdot UF + b \tag{24.2}$$

$$\theta = \exp^{a \cdot UF + b} \tag{24.3}$$

$$\theta = \frac{1}{a \cdot UF + b} \tag{24.4}$$

An impression of the expected range of θ was provided by moisture retention curves (Appendix 25) obtained from samples collected within 10 cm from the access tubes at the end of the study. During the wet season θ can be expected to be at or just below field capacity (pF=1.7–2) whereas it may approach wilting point (pF=4.2) after several dry weeks during the dry season. This range was compared to that calculated from extremes of the UF for each soil layer and more realistic regression lines were calculated when the two ranges differed much from eachother.

The air–soil interface strongly influenced the frequency measurements taken at depths above 10 cm. As such samples collected above a depth of 8 cm were excluded from the calibrations for deeper soil layers and when necessary separate calibrations were made for the 0–10 cm soil layer by combining the data of several access tubes.

24.2 Calibrations for Grassland

Regression equations for the two access tubes installed at the grassland site are given in Table 24.1, whereas plots of the predicted and the observed θ profiles against depth are shown in Figure 24.3. Both tubes were installed with their lower ends in the massive lower C-horizon.

Table 24.1: *Regression constants (a, b), standard errors (SE) and coefficients of determination (CD) for the calibrations of access tubes G1 and G2 in grassland. The sample size is represented by n.*

Tube	Depth (cm)	Model	a	SE	b	SE	CD	n	Samples used (Tube: Depths in cm)
G1	0-10	Reciprocal	-15.8611	1.5582	18.3781	1.4691	0.90	13	G1: 0-46
	10-46	Exponential	5.5638	0.9355	-6.4926	0.0736	0.81	10	G1: 10-46
	50-66	Linear	3.0054	0.3142	-2.5394	0.3044	0.95	7	G1: 22-26,50-66
	70-98	Linear	3.7210	0.3582	-3.2147	0.3463	0.93	10	G1: 22-26,70-98
	102-11	Linear	6.4096	1.1125	-5.7566	1.0645	0.89	6	G1: 22-26,102-114
G2	0-58	Reciprocal	-30.7804	2.3621	32.9560	2.2227	0.93	14	G2: 6-58
	62-82	Reciprocal	-55.6328	6.7779	56.8743	6.5668	0.91	9	G2: 30-38,62-82
	86-110	Reciprocal	-83.2930	27.8593	83.1707	26.9112	0.64	7	G2: 86-110

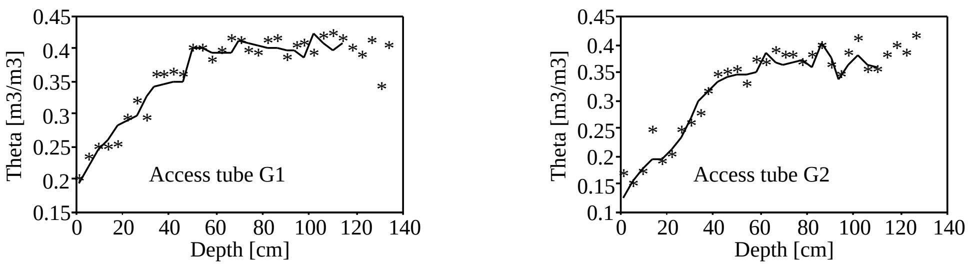


Figure 24.3: *Profiles of observed and predicted θ values for access tubes G1 and G2.*

Although the distance between the access tubes was only 5 m the calibration data could not be combined as observed θ values at a given UF differed by more than 0.05 m^3 m^{-3} between tubes G1 and G2 (Figure 24.1), illustrating the sensitivity of the probe to small variations in the properties of the soil.

24.3 Calibrations for Oleolega Drainage Basin

Regression equations for the two access tubes installed in the Oleolega drainage basin are given in Table 24.2, whereas plots of the predicted and the observed θ profiles against depth are shown in Figure 24.4. Access tube O1 was installed in undisturbed 16 year old forest whereas tube O2 was installed some 30 m to the East in an area logged in January and burned in August 1990 (bare soil). Both access tubes were installed with their lower ends in bedrock which was reached at 110 cm and 54 cm for access tubes O1 and O2 respectively. The tubes were installed in soils having similar aspects and slopes. Additional calibration data were

Table 24.2: *Regression constants (a, b), standard errors (SE) and coefficients of determination (CD) for the calibrations of access tubes O1 and O2 in the Oleolega drainage basin. The sample size is represented by n.*

Tube	Depth (cm)	Model	a	SE	b	SE	CD	n	Samples used (Tube: Depths in cm)
O1	0-10	Exponential	8.6019	2.4625	-9.3809	0.1607	0.67	8	O1: 2-10, O2: 2-6
	14-18	Exponential	14.6879	1.4191	-15.4523	0.1006	0.80	28	O1: 10-66
	22-66	Exponential	21.6394	1.5655	-22.1716	0.0658	0.90	24	O1: 22-66
	70-118	Exponential	23.5529	0.9933	-24.2214	0.0342	0.97	21	O1: 70-114
O2	0-10	Exponential	8.6019	2.4625	-9.3809	0.1607	0.67	8	O1: 2-10, O2: 2-6
	10-22	Exponential	19.3963	2.2180	-20.1997	0.0525	0.92	8	O2: 10-22
	26-30	Exponential	53.9976	10.7354	-54.3964	0.0588	0.89	5	O2: 26-30,54
	34-50	Exponential	48.4107	28.6284	-49.0202	0.0792	0.26	10	O2: 34-50

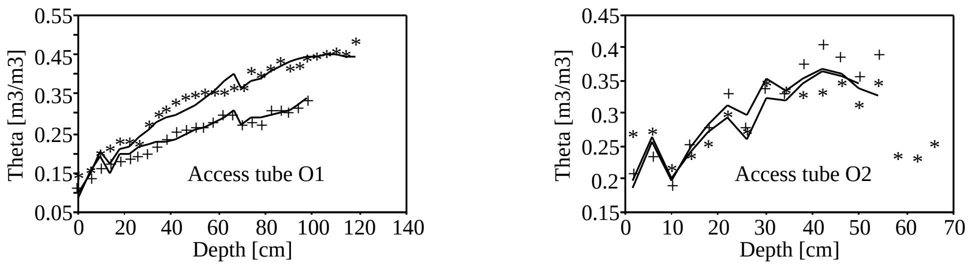


Figure 24.4: *Profiles of observed and predicted θ values for access tubes O1 and O2 in the Oleolega drainage basin*

obtained for both access tubes at the end of the study.

24.4 Calibrations for Tulasewa Forest

Regression equations for the five access tubes installed in Tulasewa forest are given in Table 24.3. Profiles of the predicted and the observed θ *versus* depth are shown in Figure 24.5 for each of the access tubes. Access tube A2 was installed with its lower end in bedrock (75 cm) whereas the other tubes were installed in the lower C-horizon or rotten rock. Dark brown A-horizons were present at tubes A1 and A2 but these had been removed by erosion at the other tubes exposing the B- or C-horizon.

Table 24.3: *Regression constants (a, b), standard errors (SE) and coefficients of determination (CD) for the calibration of access tubes A1–A5 in Tulasewa forest. The sample size is represented by n.*

Tube	Depth (cm)	Model	a	SE	b	SE	CD	n	Samples used (Tube: Depths in cm)
A1	2-6	Exponential	7.3992	4.8335	-8.3165	0.2465	0.37	6	A1-A2: 2-6
	10-38	Exponential	10.1689	1.2144	-10.9691	0.0865	0.83	16	A1: 0-38
	42-78	Exponential	8.2452	0.8521	-8.9056	0.0496	0.84	20	A1: 42-78
	82-118	Exponential	17.5237	8.1086	-18.1187	0.0921	0.26	15	A1: 82-118
A2	2-6	Exponential	7.3992	4.8335	-8.3165	0.2465	0.37	6	A1-A2: 2-6
	10-38	Exponential	10.0971	0.8510	-10.8902	0.1158	0.85	26	A1: 10-38, A2: 2-38
	42-70	Exponential	21.0294	2.8665	-21.7726	0.1287	0.86	11	A1: 110-118, A2: 42-70
A3	2-6	Exponential	2.5984	0.5972	-3.4789	0.0649	0.76	8	A3-A5: 1-6
	10-38	Exponential	4.5958	1.0010	-5.0744	0.0881	0.78	8	A3: 10-38
	42-70	Exponential	10.8990	1.1291	-11.3765	0.0795	0.90	12	A4: 6-10, A3: 42-70
	74-106	Exponential	9.5349	2.4968	-10.1331	0.0465	0.57	13	A1: 66-78, A3: 74-106
A4	2-6	Exponential	2.5984	0.5972	-3.4789	0.0649	0.76	8	A3-A5: 1-6
	10-34	Exponential	9.7456	1.1846	-10.3904	0.0680	0.72	28	A1: 54-78, A4: 10-34
	38-74	Exponential	31.9333	5.0322	-32.2289	0.0408	0.69	20	A4: 38-74
	78-98	Linear	10.8744	0.2944	-10.2856	0.0088	0.99	13	A3: 90-106, A4: 78-98
A5	2-6	Exponential	2.5984	0.5972	-3.4789	0.0649	0.76	8	A3-A5: 1-6
	0-18	Exponential	8.0433	2.2813	-8.6647	0.0953	0.76	6	A3: 42-46, A5: 6-18
	22-106	Exponential	15.2363	1.7346	-15.7284	0.0552	0.74	29	A1: 54-78, A5: 22-106

24.5 Calibrations for Korokula Forest

Regression equations for the five access tubes installed in Korokula forest are given in Table 24.6. Profiles of the predicted and the observed θ *versus* depth are shown in Figure 24.6. All access tubes were placed with their lower ends in bedrock of which the depth varied from 40 cm for access tube B3 to 80 cm for access tubes B1, B2 and B5. A sandy A-horizon was present at access tubes B1, B2, B3 and B4 but this horizon had locally been removed by erosion at tube B5. The sandy soil extended down to bedrock at tube B3 whereas a clayey B-horizon was observed at tubes B1, B2 and B5. Data from comparable soil layers of access tubes B1, B4 and B5 were combined to improve calibrations. Additional calibration data were obtained for access tubes B1 and B2 following the procedure given in Section 24.1 whereas a third set was obtained for access tube B1 from soil samples collected some 50 cm downslope from the tube. Fictional calibration points where used to improve the calibrations for the dry sandy topsoils of access tube B2 and B3 (10-38 cm) using values of θ at saturation ($UF = 1$) of 0.40 and 0.45 respectively.

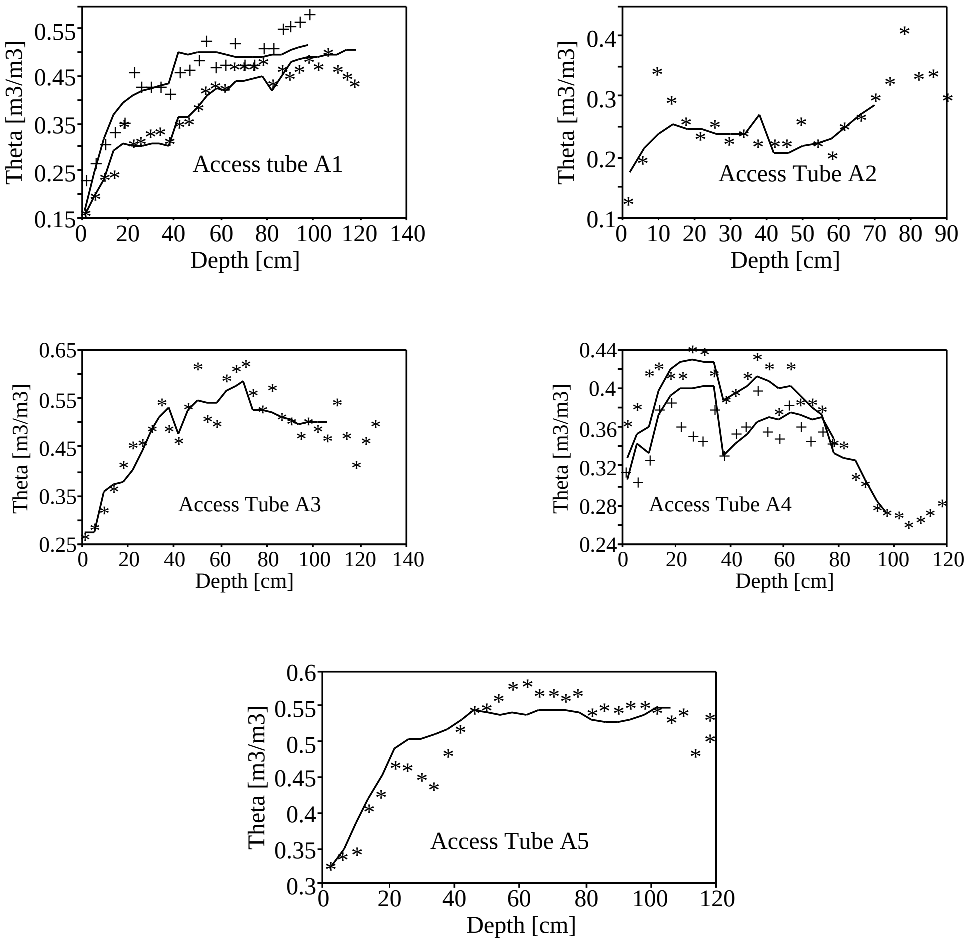


Figure 24.5: *Plot of observed and predicted θ values* versus *depth for access tubes A1–A5.*

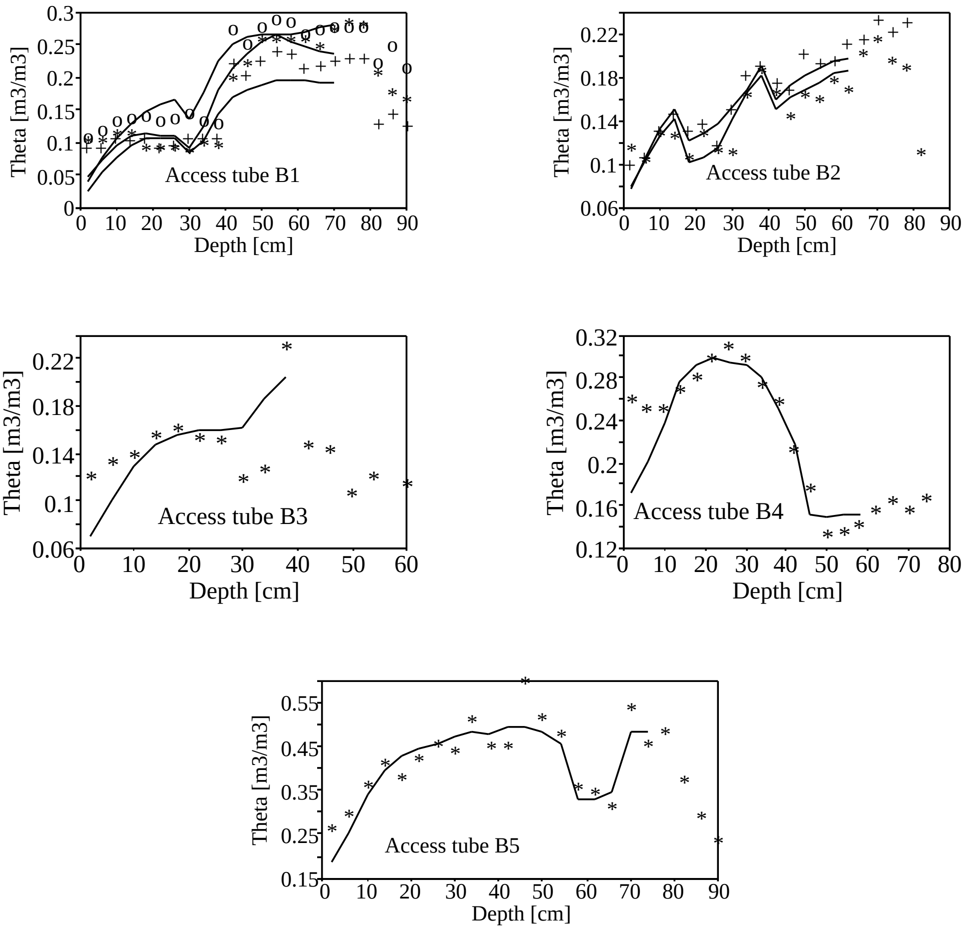


Figure 24.6: *Plot of observed and predicted θ values* versus *depth for access tubes B1–B5.*

Table 24.4: *Regression constants (a, b), standard errors (SE) and coefficients of determination (CD) for the calibration of access tubes B1–B5 in Korokula forest. The sample size is represented by n.*

Tube	Depth (cm)	Model	a	SE	b	SE	CD	n	Samples used (Tube: Depths in cm)
B1	0-26	Exponential	9.7592	0.8786	-10.5756	0.1611	0.87	20	B1: 10-26, B4: 10-26
	30-70	Exponential	9.9361	1.1357	-11.0215	0.2103	0.71	33	B1: 30-70
B2	0-14	Exponential	9.6126	1.4319	-10.8366	0.1866	0.68	17	B2: 10-38
	18-38	Exponential	14.6873	1.4319	-15.6497	0.1153	0.91	13	B2: 18-38
	42-62	Linear	2.1986	0.7106	-1.9562	0.0153	0.49	12	B2: 42-62
B3	0-38	Exponential	8.9146	2.0222	-9.9413	0.2263	0.71	10	B3: 10-38
B4	0-42	Exponential	8.9500	1.0750	-9.7501	0.0375	0.91	9	B4: 10-42
	46-58	Exponential	8.8734	0.9158	-9.9458	0.1006	0.87	16	B1: 46-58, B4: 46-58
B5	0-54	Exponential	11.0017	2.7207	-11.5720	0.0925	0.58	14	B5: 10-54,70-74
	58-66	Linear	2.9083	0.3351	-2.5173	0.0182	0.90	10	B5: 58-66, B1: 50-70
	70-74	Exponential	11.0017	2.7207	-11.5720	0.0925	0.58	14	B5: 10-54,70-74

24.6 Calibrations for Koromani Forest

Regression equations for the five access tubes installed in Koromani forest are given in Table 24.5. Profiles of the predicted and the observed θ *versus* depth are shown in Figures 24.7. Access tube C1 (ridge) and C3 (valley) were installed with their lower ends in bedrock whereas the lower ends of the other tubes were placed in a massive part of the C-horizon. The soil at access tube 3 was more sandy than those at the other tubes which explained the lower moisture content.

Table 24.5: *Regression constants (a, b), standard errors (SE) and coefficients of determination (CD) for the calibration of access tubes C1–C5 in Koromani forest. The sample size is represented by n.*

Tube	Depth (cm)	Model	a	SE	b	SE	CD	n	Samples used (Tube: Depths in cm)
C1	0-42	Exponential	10.7958	0.7060	-11.5199	0.0548	0.95	14	C1: 2-42,78-86
	46-74	Linear	3.1780	0.4622	-2.6881	0.0069	0.89	8	C1: 46-74
	78-86	Exponential	10.7958	0.7060	-11.5199	0.0548	0.95	14	C1: 2-42,78-86
C2	0-10	Exponential	4.4933	1.1883	-5.5845	0.1630	0.47	18	C1,C2,C3,C4,C5: 0-10
	10-30	Exponential	12.1463	3.0695	-12.8365	0.1061	0.76	7	C2: 10-34
	30-54	Exponential	15.6159	1.6588	-16.1760	0.0502	0.92	10	C2: 18-54
	58-70	Exponential	12.0767	3.9753	-12.8373	0.0747	0.75	5	C2: 26,58-70
C3	0-26	Exponential	5.0747	2.1916	-6.5158	0.0606	0.43	9	C3: 14,22-50
	30-50	Exponential	33.6583	23.5970	-34.0530	0.0659	0.34	6	C3: 30-50
	54-74	Exponential	16.9402	68.6840	-17.7903	0.0295	0.02	5	C3: 54-66,74
C4	0-10	Exponential	4.4933	1.1883	-5.5845	0.1630	0.47	18	C1,C2,C3,C4,C5: 0-10
	14-34	Exponential	7.3446	1.0438	-8.2058	0.0438	0.83	12	C4: 10-38
	38-50	Exponential	16.0979	4.8543	-16.6575	0.0535	0.65	8	C4: 38-50
	54-78	Exponential	20.5657	4.4372	-20.9392	0.0304	0.73	10	C4: 14-22,54-78
C5	0-34	Exponential	5.6962	0.9579	-6.6932	0.0889	0.73	15	C5: 10-34
	38-62	Exponential	17.0979	3.5363	-17.7251	0.0737	0.59	18	C5: 34-62
	66-90	Linear	10.4134	2.0792	-9.7471	0.0140	0.68	14	C4: 62-78, C5: 66-90
	94-110	Linear	3.7719	0.3591	-3.2458	0.0224	0.94	9	C4,C5: 10-15, C5: 94-110

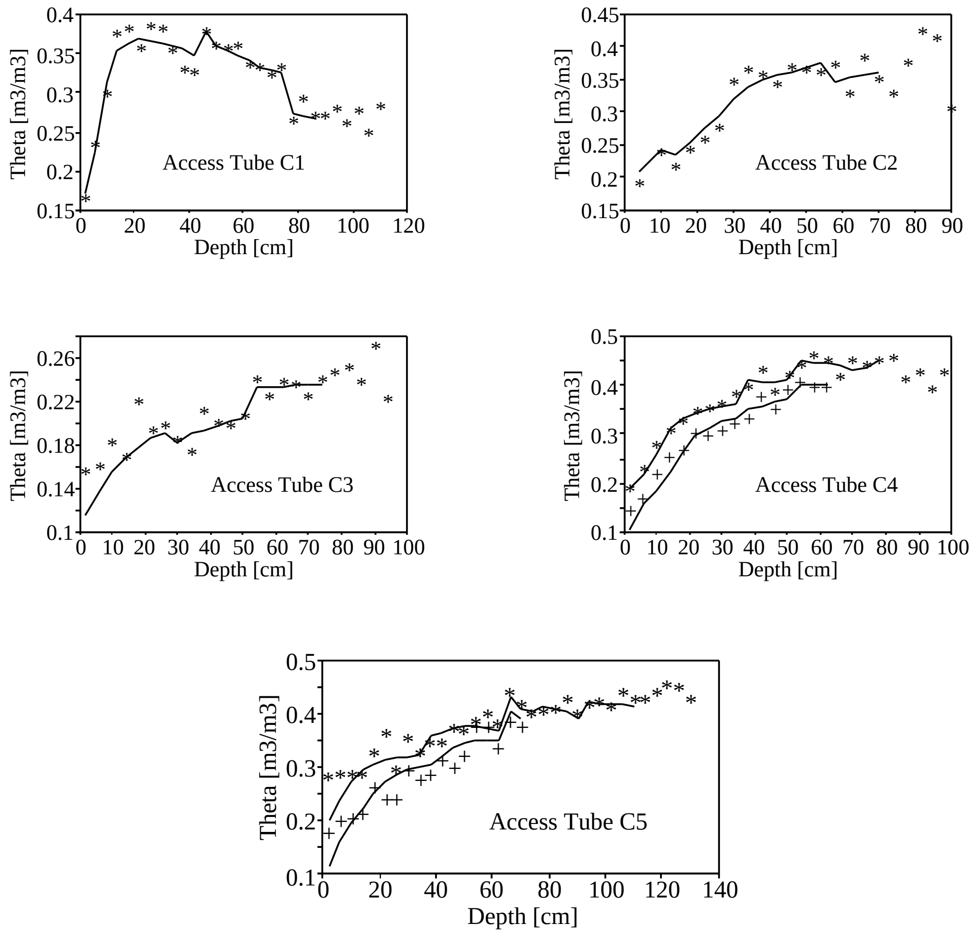


Figure 24.7: *Plot of observed and predicted θ values* versus *depth for access tubes C1–C5.*

Chapter 25

Soil Physical Data

Data on the bulk density, soil moisture retention characteristics (pF=0.4–pF=5.5) and saturated and unsaturated hydraulic conductivity for soils in Nabou forest are presented in this appendix. The data were obtained from 141 soil cores collected at several depths in Nabou grassland, Tulasewa, Korokula and Koromani forests and in the Oleolega catchment.

The 'van Genuchten' model (van Genuchten, 1980) was used to provide estimations of θ and of the unsaturated hydraulic conductivity from measured pF–θ pairs and saturated hydraulic conductivities.

The equations in the model of 'van Genuchten' are largely based on the method of Mualem (1976). The model is based on Equation 25.1 which describes the relationship between the volumetric moisture content (θ) and the pressure head (h).

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} \tag{25.1}$$

In this equation θ_r and θ_s represent the residual and saturated soil moisture contents, respectively, whereas α and n are fitting constants determining the shape of the curve. The parameter m is related to n as shown in Equation 25.2.

$$m = 1 - \frac{1}{n} \tag{25.2}$$

Estimates of θ_r and θ_s were obtained from measurements of θ on airdry (pF=5.5–6.5) and moist (pF=0.4) samples respectively, and a computer program was used to fit a curve on the experimental data by adjusting α and n using a non-linear regression technique (Marquardt, 1963). When a good fit is obtained α and n can be inserted in Equation 25.3 to obtain estimates of the unsaturated hydraulic conductivity (K_u) from the measured saturated hydraulic conductivity (K_s.

$$K_u = K_s \frac{\{1 - (\alpha h)^{n-1}[1 + (\alpha h)^n]^{-m}\}^2}{[1 + (\alpha h)^n]^{m/2}} \tag{25.3}$$

The bulk density, soil moisture retention data and available moisture for plants for eight samples in Nabou grassland are presented in Table 25.1 whereas the saturated and modelled unsaturated hydraulic conductivity data are shown in Table 25.2. Samples coded as GSMP1 were collected within 30 cm of the capacitance probe access tube 1, whereas those coded as G1 were collected in a soil pit.

The bulk density, soil moisture retention data and available moisture for plants for 30 samples collected in Tulasewa forest are presented in Table 25.3 whereas the saturated and modelled unsaturated hydraulic conductivity data are shown in Table 25.4. Samples coded as ASMP were collected within 30 cm of the capacitance probe access tubes, whereas those coded as A close to the soil pit.

The bulk density, soil moisture retention data and available moisture for plants for 22 samples collected in Korokula forest are presented in Table 25.5 whereas the saturated and

Table 25.1: *Bulk density (g cm^{-3}) and soil moisture retention data (θ in m^3 m^{-3}) for soil samples collected in Nabou grassland. Modelled θ values are shown in italics.*

Sample	Depth	Bd	Theta at various soil moisture tensions (pF)										A.M.P.
Code	cm	g/cm3	**0.4**	**1.0**	**1.4**	**1.7**	**2.0**	**2.4**	**2.7**	**3.5**	**4.2**	**Air**	m3/m3
GSMP1	4.5	1.16	0.440	0.398	0.376	0.358	0.344	0.313	0.297	0.258	0.199	0.022	0.145
GSMP1	12.5	1.20	0.421	0.412	0.372	0.340	0.316	0.278	0.263	0.249	0.191	0.021	0.125
GSMP1	19.0	1.15	0.438	0.420	0.371	0.333	0.309	0.274	0.259	0.217	0.169	0.017	0.140
G1	3.5	1.17	0.465	0.427	0.391	0.352	0.309	*0.261*	*0.228*	*0.160*	*0.119*	*0.072*	0.190
G1	13.5	1.05	0.503	0.432	0.377	0.352	0.335	0.300	0.282	0.239	0.174	0.022	0.161
G1	24.5	1.31	0.372	0.364	0.336	0.302	0.277	0.242	0.230	*0.170*	*0.136*	0.019	0.141
G1	38.5	1.28	0.392	0.379	0.351	0.318	0.296	0.271	0.263	*0.208*	*0.174*	0.02	0.122
G1	61.5	1.33	0.359	0.336	0.313	0.291	0.272	0.249	0.242	*0.199*	*0.171*	0.021	0.101

Bd: Bulk density, Air: Theta of air dry soil (pF between 5 and 6)
A.M.P.: Available moisture for plants (Field capacity (pF=2) minus capacity at wilting point (pF=4.2))

Table 25.2: *Measured saturated hydraulic conductivities (mm day^{-1}), model parameters and correlation coefficients (r), and modelled unsaturated hydraulic conductivities (mm day^{-1}) for soil samples collected in Nabou grassland.*

Sample	Depth	K-sat	Model parameters					Modelled K-unsat			
Code	cm	mm/d	Tsat* m3/m3	Tres* m3/m3	Alpha	n	r	pF=1 mm/d	pF=2 mm/d	pF=3 mm/d	pF=4.2 mm/d
GSMP1	4.5	22400	0.45	0.02	0.1916	1.1032	0.96	28.34	0.24	0.00	0.00
GSMP1	12.5	950	0.45	0.02	0.2586	1.1094	0.95	0.67	0.01	0.00	0.00
GSMP1	19.0	6400	0.47	0.02	0.2475	1.1320	0.98	7.29	0.05	0.00	0.00
G1	3.5	12800	0.47	0.02	0.0717	1.2149	0.99	273.20	2.41	0.00	0.00
G1	13.5	160500	0.58	0.02	1.1766	1.1234	0.98	6.10	0.03	0.00	0.00
G1	24.5	2800	0.38	0.02	0.6530	1.1637	0.98	44.22	0.53	0.00	0.00
G1	38.5	430	0.40	0.02	0.1080	1.1209	0.97	1.90	0.00	0.00	0.00
G1	61.5	71	0.37	0.02	0.2003	1.1042	0.99	0.08	0.00	0.00	0.00

*: Tsat, Tres are theta at saturation and residual theta respectively

Table 25.3: *Bulk density ($g\ cm^{-3}$) and soil moisture retention data (θ in $m^3\ m^{-3}$) for soil samples collected in Tulasewa forest. Modelled θ values are shown in italics.*

Sample Code	Depth cm	Bd g/cm3	Theta at various soil moisture tensions (pF)										A.M.P. m3/m3
			0.4	**1.0**	**1.4**	**1.7**	**2.0**	**2.4**	**2.7**	**3.5**	**4.2**	**Air**	
ASMP1	3.5	1.17	0.597	0.587	0.582	0.567	0.550	0.521	0.500	0.504	0.422	0.092	0.128
ASMP1	40.0	0.94	0.652	0.650	0.649	0.648	0.642	0.621	0.603	0.527	0.431	0.092	0.211
ASMP1	65.0	1.03	0.679	0.672	0.670	0.669	0.665	0.651	0.641	0.580	0.561	0.140	0.104
ASMP2	3.5	0.88	0.637	0.579	0.551	0.539	0.514	0.477	0.459	0.344	0.265	0.068	0.249
ASMP3	3.5	1.13	0.589	0.573	0.535	0.504	0.478	0.433	0.412	*0.340*	*0.290*		0.188
ASMP3	29.0	0.91	0.695	0.671	0.660	0.650	0.641	0.627	0.620	*0.594*	*0.573*		0.068
ASMP3	72.0	1.06	0.738	0.739	0.735	0.730	0.721	0.704	0.693	*0.651*	*0.615*	0.048	0.106
ASMP4	3.5	1.29	0.566	0.556	0.552	0.532	0.507	0.462	0.435	0.388	0.313	0.058	0.194
ASMP4	40.5	1.34	0.562	0.553	0.552	0.550	0.545	0.512	0.487	0.381	0.239	0.052	0.306
ASMP4	65.5	1.26	0.597	0.580	0.566	0.545	0.524	0.478	0.454	0.289	0.161	0.056	0.363
ASMP5	3.5	1.13	0.582	0.541	0.499	0.482	0.457	0.417	0.397	0.308	0.220	0.055	0.238
ASMP5	17.5	1.22	0.575	0.561	0.530	0.516	0.499	0.462	0.439	0.390	0.317	0.082	0.181
ASMP5	24.5	1.30	0.585	0.584	0.587	0.585	0.572	0.553	0.540	0.428	0.367	0.091	0.204
ASMP5	60.5	1.00	0.644	0.637	0.631	0.625	0.615	0.597	0.587	*0.555*	*0.528*		0.087
A1	2.5	0.91	0.633	0.603	0.570	0.539	0.525	*0.435*	*0.390*	0.284	0.230	0.085	0.295
A2	14.5	1.16	0.564	0.535	0.506	0.478	0.471	*0.368*	*0.314*	0.436	0.326	0.088	0.145
A3	14.0	1.08	0.553	0.527	0.495	0.469	0.460	*0.405*	*0.372*	0.436	0.326		0.134
A4	30.5	0.98	0.599	0.580	0.545	0.517	0.506	*0.411*	*0.361*	*0.254*	*0.190*	0.113	0.316
A5	37.5	0.89	0.617	0.588	0.551	0.525	0.515	*0.463*	*0.428*	0.413	0.325	0.112	0.190
A6	42.5	0.81	0.637	0.620	0.582	0.555	0.537	*0.479*	*0.436*	0.382	0.292	0.105	0.245
A7	48.5	0.79	0.653	0.622	0.579	0.548	0.532	*0.464*	*0.423*	0.377	0.289	0.104	0.243
A8	57.5	0.73	0.651	0.604	0.557	0.527	0.506	*0.434*	*0.395*	0.345	0.270	0.098	0.236
A9	62.5	0.78	0.626	0.574	0.528	0.501	0.487	*0.42*	*0.386*	0.362	0.281	0.096	0.206
A10	68.5	0.92	0.664	0.642	0.594	0.566	0.552	*0.478*	*0.437*	0.360	0.297	0.141	0.255
A11	74.5	0.91	0.623	0.600	0.561	0.538	0.528	*0.487*	*0.456*	0.450	0.371	0.145	0.157
A12	97.5	1.04	0.662	0.652	0.628	0.606	0.596	*0.622*	*0.601*	0.473	0.334	0.153	0.262
A13	110.5	1.09	0.660	0.658	0.645	0.619	0.607	*0.623*	*0.593*	0.429	0.310	0.108	0.297
A14	126.5	1.01	0.666	0.660	0.624	0.589	0.567	*0.505*	*0.456*	0.379	0.274	0.124	0.293
A15	137.5	1.04	0.633	0.627	0.588	0.557	0.533	*0.479*	*0.435*	0.375	0.267	0.120	0.266
A16	148.5	1.30	0.516	0.494	0.485	0.476	0.473	*0.494*	*0.492*	0.435	0.371	0.137	0.102

Bd: Bulk density, Air: Theta of air dry soil (pF between 5 and 6)
A.M.P.: Available moisture for plants (Field capacity (pF=2) minus capacity at wilting point (pF=4.2))

Table 25.4: *Measured saturated hydraulic conductivities (mm day^{-1}), model parameters and correlation coefficients (r), and modelled unsaturated hydraulic conductivities (K-unsat, mm day^{-1}) for soil samples collected in Tulasewa forest.*

Sample Code	Depth cm	K-sat mm/d	Model parameters Tsat* m3/m3	Tres* m3/m3	Alpha	n	r	Modelled K-unsat pF=1 mm/d	pF=2 mm/d	pF=3 mm/d	pF=4.2 mm/d
ASMP1	3.5	18	0.60	0.07	0.0411	1.0650	0.99	0.100	0.003	0.000	0.000
ASMP1	40.0	0.09	0.65	0.01	0.0019	1.1197	0.99	0.013	0.003	0.000	0.000
ASMP1	65.0	0.01	0.68	0.12	0.0079	1.0517	0.96	0.000	0.000	0.000	0.000
ASMP2	3.5	101000	0.67	0.01	0.1530	1.1050	0.92	192	1.82	0.010	0.000
ASMP3	3.5	1840	0.59	0.10	0.0607	1.1359	0.99	23.5	0.340	0.000	0.000
ASMP3	29.0	0.60	0.72	0.01	1.3662	1.0226	0.99	0.000	0.000	0.000	0.000
ASMP3	72.0	0.01	0.74	0.15	0.0108	1.0463	0.99	0.000	0.000	0.000	0.000
ASMP4	3.5	7.7	0.57	0.01	0.0269	1.0979	0.99	0.143	0.005	0.000	0.000
ASMP4	40.5	1.12	0.56	0.01	0.0021	1.2319	0.98	0.391	0.113	0.004	0.000
ASMP4	65.5	31	0.60	0.01	0.0071	1.2533	0.96	7.5	0.858	0.006	0.000
ASMP5	3.5	32000	0.60	0.01	0.0986	1.1214	0.96	165	1.76	0.009	0.000
ASMP5	17.5	2200	0.58	0.01	0.0614	1.0838	0.98	11.8	0.206	0.001	0.000
ASMP5	24.5	0.28	0.59	0.01	0.0030	1.1294	0.99	0.037	0.008	0.000	0.000
ASMP5	60.5	6.7	0.65	0.15	0.0381	1.0420	0.99	0.018	0.000	0.000	0.000
A1	2.5	19200	0.64	0.08	0.0306	1.2114	0.99	1176	25.7	0.100	0.000
A2	14.5	27100	0.56	0.07	0.0170	1.3189	0.98	5271	202.6	0.547	0.000
A3	14.0	1010	0.56	0.01	0.4890	1.1287	0.83	15.2	0.264	0.001	0.000
A4	30.5	490	0.60	0.05	0.0219	1.2335	0.99	48.7	1.5	0.006	0.000
A5	37.5	20200	0.63	0.01	0.0478	1.1206	0.85	286	0.053	0.031	0.000
A6	42.5	220	0.64	0.01	0.0255	1.1508	0.93	9.2	0.286	0.002	0.000
A7	48.5	1200	0.66	0.01	0.4640	1.1428	0.93	23.7	0.415	0.002	0.000
A8	57.5	29800	0.67	0.01	0.0823	1.1425	0.94	265.5	2.9	0.014	0.000
A9	62.5	7700	0.65	0.01	0.1339	1.1259	0.90	25.4	0.223	0.001	0.000
A10	68.5	4900	0.67	0.01	0.0451	1.1400	0.97	96.8	1.76	0.009	0.000
A11	74.5	1600	0.63	0.01	0.0467	1.1038	0.80	17.9	0.358	0.002	0.000
A12	97.5	2.7	0.64	0.01	0.0009	1.2544	0.97	1.3	0.578	0.052	0.000
A13	110.5	1.4	0.65	0.01	0.0012	1.2816	0.98	0.710	0.290	0.018	0.000
A14	126.5	84	0.67	0.01	0.0204	1.1646	0.97	5.0	0.192	0.001	0.000
A15	137.5	12	0.64	0.01	0.0221	1.1568	0.96	0.615	0.022	0.000	0.000
A16	148.5	2.5	0.50	0.00	0.0001	1.3479	0.96	2.0	1.52	0.665	0.014

*: Tsat, Tres are theta at saturation and residual theta respectively

Table 25.5: *Bulk density (g cm^{-3}) and soil moisture retention data (θ in m^3 m^{-3}) for soil samples collected in Korokula forest. Modelled θ values are shown in italics.*

Sample Code	Depth cm	Bd g/cm3	Theta at various soil moisture tensions (pF) 0.4	1.0	1.4	1.7	2.0	2.4	2.7	3.5	4.2	Air	A.M.P. m3/m3
BSMP1	22.5	1.30	0.437	0.417	0.405	0.383	0.365	0.297	0.258	*0.181*	*0.133*		0.232
BSMP1	70.5	1.61	0.517	0.514	0.513	0.512	0.509	0.496	0.486	0.469	0.445	0.039	0.064
BSMP2	53.5	1.78	0.405	0.402	0.399	0.383	0.363	0.333	0.320	0.297	0.263	0.033	0.099
BSMP3	3.5	1.36	0.475	0.467	0.419	0.395	0.377	0.343	0.324	*0.271*	*0.233*		0.144
BSMP3	12.5	1.35	0.469	0.454	0.392	0.361	0.343	0.304	0.282	*0.222*	*0.183*		0.160
BSMP4	3.5	1.23	0.481	0.459	0.423	0.391	0.369	0.322	0.292	*0.230*	*0.187*		0.182
BSMP4	12.5	1.37	0.449	0.437	0.378	0.340	0.315	0.270	0.247	*0.180*	*0.141*		0.174
BSMP4	18.5	1.22	0.449	0.422	0.363	0.327	0.302	0.249	0.228	*0.164*	*0.127*		0.175
BSMP5	4.5	1.40	0.438	0.424	0.405	0.369	0.342	0.298	0.275	*0.208*	*0.166*		0.176
BSMP5	12.5	1.28	0.568	0.554	0.526	0.501	0.481	0.445	0.425	*0.365*	*0.320*		0.161
BSMP5	51	1.57	0.494	0.478	0.468	0.447	0.431	0.405	0.393	*0.349*	*0.319*		0.112
B1	3.5	1.14	0.522	0.480	0.422	0.377	0.359	*0.260*	*0.218*	*0.136*	*0.093*	0.022	0.266
B1	11.5	1.32	0.477	0.444	0.395	0.353	0.338	*0.254*	*0.216*	*0.141*	*0.100*	0.026	0.238
B2	3.5	1.07	0.452	0.384	0.313	0.276	0.259	*0.196*	*0.169*	*0.115*	*0.084*	0.021	0.175
B2	11.5	1.21	0.500	0.430	0.349	0.300	0.281	*0.212*	*0.180*	*0.118*	*0.082*	0.024	0.199
B3	3.5	1.16	0.555	0.489	0.425	0.389	0.370	*0.272*	*0.232*	*0.152*	*0.106*	0.023	0.264
B3	11.5	1.15	0.498	0.429	0.370	0.332	0.315	*0.238*	*0.207*	*0.143*	*0.105*	0.020	0.210
soilpit	3.5	1.15	0.465	0.419	0.367	0.346	0.320	*0.249*	*0.216*	0.142	0.117	0.027	0.203
soilpit	28	1.36	0.390	0.376	0.329	0.294	0.267	*0.233*	*0.207*	0.190	0.112	0.020	0.155
soilpit	53	1.40	0.528	0.533	0.525	0.492	0.485	*0.454*	*0.432*	0.378	0.332	0.115	0.153
soilpit	72	1.38	0.520	0.520	0.494	0.468	0.459	*0.425*	*0.404*	*0.354*	0.316	0.110	0.143
soilpit	87	1.44	0.510	0.514	0.503	0.473	0.464	*0.422*	*0.391*	*0.318*	0.268	0.102	0.196

Bd: Bulk density, Air: Theta of air dry soil (pF between 5 and 6)
A.M.P.: Available moisture for plants (Field capacity (pF=2) minus capacity at wilting point (pF=4.2))

modelled unsaturated hydraulic conductivity data are shown in Table 25.6. Samples coded as BSMP were collected within 30 cm of the capacitance probe acces tubes.

The bulk density, soil moisture retention data and available moisture for plants for 22 samples collected in Koromani forest are presented in Table 25.7 whereas the saturated and modelled unsaturated hydraulic conductivity data are shown in Table 25.8. Samples coded as CSMP were collected within 30 cm of the capacitance probe acces tubes.

The bulk density, soil moisture retention data and available moisture for plants for 25 samples, collected within the forested Oleolega drainage basin before logging started, are presented in Table 25.9 whereas the saturated and modelled unsaturated hydraulic conductivity data are shown in Table 25.10. Samples coded as OSMP were collected within 30 cm of the capacitance probe acces tubes. Samples were collected at the same locations after logging and burning of the catchment and the results are presented in Tables 25.11 and 25.12 respectively. Additional samples were collected on skidder tracks, roads and landings in the vicinity of the previous sample points to study the effect of compression and removal of the top soil on the moisture retention characteristics, permeability and bulk density. The results for the samples collected on the skidder tracks, roads and landings are given in Tables 25.13 and 25.14.

Table 25.6: *Measured saturated hydraulic conductivities (mm day^{-1}), model parameters and correlation coefficients (r), and modelled unsaturated hydraulic conductivities (mm day^{-1}) for soil samples collected in Korokula forest.*

Sample Code	Depth	K-sat	Model parameters						Modelled K-unsat		
			Tsat*	Tres*	Alpha	n	r	pF=1	pF=2	pF=3	pF=4.2
	cm	mm/d	m3/m3	m3/m3				mm/d	mm/d	mm/d	mm/d
BSMP1	22.5	220	0.44	0.03	0.0216	1.2358	0.97	22.0	0.710	0.003	0.000
BSMP1	70.5	0.04	0.52	0.04	0.0138	1.0302	0.98	0.000	0.000	0.000	0.000
BSMP2	53.5	7.5	0.41	0.03	0.0485	1.0751	0.96	0.045	0.001	0.000	0.000
BSMP3	3.5	5880	0.50	0.03	0.1831	1.1050	0.97	8.0	0.070	0.000	0.000
BSMP3	12.5	1960	0.49	0.03	0.1568	1.1409	0.97	5.8	0.044	0.000	0.000
BSMP4	3.5	1140	0.49	0.03	0.0790	1.1506	1.00	11.8	0.129	0.001	0.000
BSMP4	12.5	920	0.46	0.03	0.0849	1.1880	0.98	12.3	0.106	0.000	0.000
BSMP4	18.5	1490	0.46	0.03	0.1009	1.2024	0.99	16.8	0.119	0.000	0.000
BSMP5	4.5	220	0.45	0.03	0.0479	1.1683	0.99	5.5	0.086	0.000	0.000
BSMP5	12.5	2100	0.58	0.03	0.0811	1.0879	1.00	8.3	0.118	0.001	0.000
BSMP5	51	0.95	0.50	0.15	0.0643	1.1034	0.99	0.007	0.000	0.000	0.000
B1	3.5	6600	0.53	0.02	0.0524	1.2890	0.97	349	3.1	0.007	0.000
B1	11.5	249500	0.49	0.02	0.5270	1.2624	0.98	11296	112	0.284	0.000
B2	3.5	34400	0.49	0.02	0.2218	1.2439	0.98	109	0.395	0.001	0.000
B2	11.5	34500	0.53	0.01	0.1772	1.2487	0.99	180	0.704	0.002	0.000
B3	3.5	52000	0.57	0.01	0.0888	1.2438	0.96	959	6.2	0.016	0.000
B3	11.5	47700	0.53	0.02	0.1651	1.2275	0.97	256	1.2	0.003	0.000
soilpit	3.5	32100	0.48	0.01	0.0827	1.2179	0.98	561	4.3	0.013	0.000
soilpit	28	10500	0.40	0.01	0.0808	1.1838	0.94	146	1.3	0.005	0.000
soilpit	53	9.2	0.54	0.12	0.0260	1.1087	0.99	0.214	0.007	0.000	0.000
soilpit	72	410	0.53	0.11	0.0599	1.1038	0.99	3.3	0.055	0.000	0.000
soilpit	87	36	0.52	0.10	0.0162	1.1642	0.99	2.6	0.128	0.001	0.000

*: Tsat, Tres are theta at saturation and residual theta respectively

Table 25.7: *Bulk density ($g\ cm^{-3}$) and soil moisture retention data (θ in $m^3\ m^{-3}$) for soil samples collected in Koromani forest. Modelled θ values are shown in italics.*

Sample Code	Depth	Bd	Theta at various soil moisture tensions (pF)										A.M.P.
	cm	g/cm3	**0.4**	**1.0**	**1.4**	**1.7**	**2.0**	**2.4**	**2.7**	**3.5**	**4.2**	**Air**	m3/m3
CSMP4	3.5	1.16	0.581	0.510	0.441	0.419	0.404	0.372	0.356	0.297	0.255	0.029	0.149
CSMP4	31.5	1.36	0.517	0.500	0.464	0.445	0.432	0.411	0.403	0.432	0.356	0.027	0.076
CSMP4	53.5	1.45	0.518	0.514	0.509	0.497	0.488	0.471	0.463	0.531	0.465	0.035	0.023
CSMP5	3.5	1.22	0.558	0.496	0.454	0.433	0.419	0.388	0.372	0.350	0.287	0.031	0.131
CSMP5	33.5	1.49	0.477	0.461	0.429	0.411	0.399	0.376	0.353	0.381	0.310	0.028	0.089
CSMP5	57.5	1.37	0.525	0.514	0.502	0.486	0.474	0.451	0.440	0.459	0.394	0.032	0.079
C1	3.5	1.08	0.492	0.460	0.434	0.423	0.419	*0.393*	*0.379*	*0.345*	*0.318*	0.046	0.101
C1	10.5	1.18	0.476	0.454	0.422	0.401	0.397	*0.389*	*0.354*	*0.316*	*0.287*	0.038	0.110
C1	16.5	1.16	0.462	0.445	0.412	0.394	0.387	*0.365*	*0.351*	*0.317*	*0.290*		0.097
C1	37.5	1.38	0.511	0.513	0.498	0.480	0.475	*0.451*	*0.434*	*0.392*	*0.358*	0.047	0.117
C1	43.5	1.37	0.501	0.498	0.483	0.469	0.461	*0.385*	*0.325*	*0.192*	*0.120*		0.341
Soil pit	3.5	1.12	0.511	0.442	0.419	0.406	0.395	*0.355*	*0.336*	0.308	0.237	0.049	0.158
Soil pit	9.5	1.19	0.518	0.443	0.406	0.378	0.362	*0.322*	*0.300*	*0.249*	*0.213*		0.149
Soil pit	15.5	1.42	0.515	0.474	0.443	0.410	0.393	*0.358*	*0.336*	*0.284*	*0.246*	0.053	0.147
Soil pit	23.5	1.43	0.512	0.493	0.455	0.425	0.405	*0.361*	*0.334*	*0.272*	0.228		0.177
Soil pit	30.5	1.29	0.508	0.459	0.417	0.392	0.379	*0.343*	*0.322*	*0.274*	*0.239*		0.140
Soil pit	57.5	1.31	0.583	0.559	0.544	0.528	0.516	*0.497*	*0.484*	*0.450*	*0.423*	0.053	0.093
Soil pit	63.5	1.32	0.544	0.535	0.512	0.492	0.479	*0.450*	*0.431*	*0.382*	*0.345*	0.050	0.134
C3	3.5	1.03	0.546	0.459	0.425	0.399	0.386	*0.342*	*0.319*	*0.267*	*0.230*	0.050	0.156
C3	21.5	1.33	0.536	0.477	0.428	0.397	0.383	*0.338*	*0.314*	*0.258*	*0.219*	0.040	0.164
C3	27.5	1.39	0.537	0.488	0.440	0.407	0.388	*0.346*	*0.321*	*0.264*	*0.224*	0.040	0.164
C3	36.5	1.36	0.517	0.473	0.420	0.387	0.375	*0.349*	*0.304*	*0.247*	*0.207*	0.040	0.168

Bd: Bulk density, Air: Theta of air dry soil (pF between 5 and 6)
A.M.P.: Available moisture for plants (Field capacity (pF=2) minus capacity at wilting point (pF=4.2))

Table 25.8: *Measured saturated hydraulic conductivities (mm day^{-1}), model parameters and correlation coefficients (r), and modelled unsaturated hydraulic conductivities (mm day^{-1}) for soil samples collected in Koromani forest.*

Sample	Depth	K-sat	Model parameters						Modelled K-unsat		
Code			Tsat*	Tres*	Alpha	n	r	pF=1	pF=2	pF=3	pF=4.2
	cm	mm/d	m3/m3	m3/m3				mm/d	mm/d	mm/d	mm/d
CSMP4	3.5	12	0.63	0.03	0.9143	1.1038	0.97	0.001	0.000	0.000	0.000
CSMP4	31.5	300	0.54	0.10	0.7092	1.0624	0.96	0.013	0.000	0.000	0.000
CSMP4	53.5	4	0.52	0.04	0.0404	1.0428	0.99	0.010	0.000	0.000	0.000
CSMP5	3.5	680	0.60	0.03	1.2333	1.0784	0.96	0.013	0.000	0.000	0.000
CSMP5	33.5	180	0.49	0.03	0.3394	1.0620	0.96	0.034	0.000	0.000	0.000
CSMP5	57.5	7	0.54	0.03	0.3033	1.0411	0.98	0.001	0.000	0.000	0.000
C1	3.5	150	0.50	0.05	0.3762	1.0597	0.89	0.022	0.000	0.000	0.000
C1	10.5	3180	0.50	0.05	0.4632	1.0719	0.95	0.416	0.003	0.000	0.000
C1	16.5	66	0.50	0.05	0.9596	1.0652	0.94	0.002	0.000	0.000	0.000
C1	37.5	110	0.52	0.05	0.0357	1.0645	0.85	0.704	0.020	0.000	0.000
C1	43.5	210	0.51	0.01	0.0078	1.3157	0.99	64.9	7.0	0.036	0.000
Soil pit	3.5	50500	0.54	0.05	0.6374	1.0936	0.95	5.1	0.034	0.000	0.000
Soil pit	9.5	7800	0.57	0.05	0.7627	1.1235	0.97	0.771	0.004	0.000	0.000
Soil pit	15.5	15500	0.54	0.05	0.2556	1.1091	0.99	12.5	0.092	0.001	0.000
Soil pit	23.5	2300	0.52	0.05	0.0820	1.1351	1.00	18.9	0.214	0.001	0.000
Soil pit	30.5	47600	0.55	0.05	0.6235	1.1058	0.98	6.0	0.037	0.000	0.000
Soil pit	57.5	250	0.60	0.03	0.4226	1.0418	1.00	0.016	0.000	0.000	0.000
Soil pit	63.5	230	0.55	0.05	0.0767	1.0744	0.97	0.729	0.011	0.000	0.000
C3	3.5	65600	0.60	0.05	0.8944	1.1171	0.94	4.3	0.024	0.000	0.000
C3	21.5	5700	0.57	0.04	0.4060	1.1240	0.98	2.2	0.013	0.000	0.000
C3	27.5	2200	0.57	0.04	0.3376	1.1233	0.99	1.22	0.008	0.000	0.000
C3	36.5	750	0.54	0.04	0.2497	1.1322	0.96	0.84	0.005	0.000	0.000

*: Tsat, Tres are theta at saturation and residual theta respectively

Table 25.9: *Bulk density ($g\ cm^{-3}$) and soil moisture retention data (θ in $m^3\ m^{-3}$) for soil samples collected in the undisturbed Oleolega drainage basin. Modelled θ values are shown in italics.*

Sample Code	Depth cm	Bd g/cm3	Theta at various soil moisture tensions (pF) 0.4	1.0	1.4	1.7	2.0	2.4	2.7	3.0	4.2	Air	A.M.P. m3/m3
OSMP1	3.5	1.15	0.479	0.441	0.403	0.378	0.355	0.308	0.280	0.193	0.127	0.022	0.228
OSMP1	32.5	1.39	0.481	0.477	0.461	0.420	0.387	0.328	0.303	0.298	0.200	0.027	0.187
OSMP1	68.5	1.43	0.487	0.476	0.457	0.438	0.422	0.387	0.370	0.321	0.216	0.026	0.206
O4	3.5	1.13	0.489	0.470	0.423	0.400	0.384	*0.345*	*0.321*	*0.299*	*0.228*	0.047	0.156
O4	27.5	1.08	0.530	0.437	0.381	0.352	0.331	*0.280*	*0.254*	*0.231*	*0.162*		0.169
O5	3.5	0.99	0.571	0.490	0.437	0.412	0.398	*0.281*	*0.255*	*0.232*	*0.160*	0.029	0.238
O5	29.5	1.15	0.553	0.512	0.473	0.434	0.404	*0.361*	*0.332*	*0.305*	*0.222*		0.182
O11	3.5	0.99	0.567	0.483	0.413	0.376	0.352	*0.298*	*0.268*	*0.242*	*0.163*	0.032	0.189
O11	31.5	1.31	0.525	0.507	0.439	0.388	0.360	*0.296*	*0.259*	*0.228*	*0.143*		0.217
O13	3.5	1.14	0.538	0.534	0.486	0.446	0.414	*0.354*	*0.315*	*0.280*	*0.177*	0.022	0.237
O13	33.5	1.25	0.538	0.522	0.470	0.426	0.401	*0.344*	*0.310*	*0.280*	*0.189*		0.212
O18	3.5	1.05	0.551	0.486	0.463	0.435	0.424	*0.388*	*0.369*	*0.350*	*0.285*	0.044	0.139
O18	28.5	1.18	0.531	0.519	0.453	0.416	0.392	*0.337*	*0.305*	*0.276*	*0.189*		0.203
O19	3.5	1.06	0.601	0.511	0.466	0.438	0.416	*0.368*	*0.341*	*0.316*	*0.236*	0.030	0.180
O19	31.5	1.11	0.533	0.493	0.424	0.374	0.344	*0.284*	*0.250*	*0.221*	*0.141*		0.203
O27	3.5	1.00	0.511	0.443	0.405	0.379	0.357	*0.321*	*0.299*	*0.278*	*0.211*	0.034	0.146
O27	31.5	1.28	0.469	0.438	0.374	0.336	0.311	*0.261*	*0.233*	*0.209*	*0.139*		0.172
O42	3.5	1.05	0.610	0.588	0.539	0.513	0.504	*0.464*	*0.441*	*0.419*	*0.343*	0.054	0.161
O42	31.5	1.11	0.603	0.548	0.491	0.457	0.440	*0.392*	*0.365*	*0.340*	*0.258*		0.182
O47	3.5	1.02	0.591	0.562	0.478	0.451	0.432	*0.373*	*0.341*	*0.312*	*0.221*	0.039	0.211
O47	27.5	1.16	0.557	0.518	0.466	0.422	0.391	*0.337*	*0.304*	*0.275*	*0.187*		0.204
O61	3.5	1.00	0.638	0.531	0.498	0.466	0.446	*0.396*	*0.369*	*0.344*	*0.260*	0.018	0.186
O61	21.5	1.21	0.522	0.434	0.380	0.350	0.332	*0.285*	*0.261*	*0.239*	*0.172*		0.160
O64	3.5	1.22	0.513	0.502	0.437	0.410	0.394	*0.345*	*0.318*	*0.292*	*0.212*	0.042	0.182
O64	34.5	1.29	0.550	0.522	0.477	0.434	0.421	*0.374*	*0.347*	*0.322*	*0.241*		0.180

Bd: Bulk density, Air: Theta of air dry soil (pF between 5 and 6)
A.M.P.: Available moisture for plants (Field capacity (pF=2) minus capacity at wilting point (pF=4.2))

Table 25.10: *Measured saturated hydraulic conductivities (mm day^{-1}), model parameters and correlation coefficients (r), and modelled unsaturated hydraulic conductivities (mm day^{-1}) for soil samples collected within the forested Oleolega drainage basin.*

Sample	Depth	K-sat	Model parameters					Modelled K-unsat			
Code			Tsat*	Tres*	Alpha	n	r	pF=1	pF=2	pF=3	pF=4.2
	cm	mm/d	m3/m3	m3/m3				mm/d	mm/d	mm/d	mm/d
OSMP1	3.5	101	0.48	0.02	0.0483	1.2094	0.95	3.6	0.048	0.000	0.000
OSMP1	32.5	56	0.49	0.03	0.0426	1.1557	0.98	1.4	0.026	0.000	0.000
OSMP1	68.5	8.8	0.49	0.03	0.0217	1.1444	0.98	0.398	0.015	0.000	0.000
O4	3.5	30600	0.50	0.05	0.1259	1.1210	0.95	105	0.977	0.005	0.000
O4	27.5	19300	0.57	0.05	0.4252	1.1742	0.96	10.2	0.045	0.000	0.000
O5	3.5	82800	0.59	0.03	0.6151	1.1585	0.97	17.3	0.079	0.000	0.000
O5	29.5	580	0.57	0.05	0.1467	1.1424	1.00	2.0	0.015	0.000	0.000
O11	3.5	27400	0.62	0.03	0.4155	1.1708	0.98	14.9	0.068	0.000	0.000
O11	31.5	1660	0.54	0.05	0.0735	1.2350	0.96	39.2	0.310	0.001	0.000
O13	3.5	8100	0.55	0.02	0.0460	1.1862	0.96	253	3.8	0.016	0.000
O13	33.5	2140	0.55	0.05	0.0704	1.1827	0.97	36.2	0.375	0.001	0.000
O18	3.5	175000	0.59	0.04	0.8227	1.0863	0.95	9.3	0.062	0.000	0.000
O18	28.5	4860	0.55	0.05	0.0927	1.1751	0.94	50.3	0.434	0.002	0.000
O19	3.5	83000	0.65	0.03	0.6285	1.1199	0.96	12.1	0.069	0.000	0.000
O19	31.5	1920	0.55	0.05	0.1088	1.2287	0.98	22.8	0.134	0.000	0.000
O27	3.5	224900	0.57	0.03	0.8685	1.1157	0.99	15.5	0.087	0.000	0.000
O27	31.5	4610	0.49	0.05	0.1318	1.2087	0.98	33.9	0.195	0.001	0.000
O42	3.5	73200	0.63	0.05	0.2213	1.0846	0.93	51.3	0.454	0.003	0.000
O42	31.5	580	0.64	0.05	0.3641	1.1206	0.98	0.268	0.002	0.000	0.000
O47	3.5	19100	0.61	0.039	0.1509	1.1467	0.91	65.0	0.481	0.002	0.000
O47	27.5	770	0.57	0.05	0.1077	1.1789	0.99	6.4	0.049	0.000	0.000
O61	3.5	142000	0.71	0.02	1.1078	1.1079	0.94	5.6	0.033	0.000	0.000
O61	21.5	580	0.60	0.05	0.8479	1.1583	0.98	0.059	0.000	0.000	0.000
O64	3.5	11200	0.53	0.04	0.1153	1.1404	0.90	56.8	0.503	0.002	0.000
O64	34.5	320	0.57	0.05	0.1557	1.1218	0.96	0.834	0.007	0.000	0.000

*: Tsat, Tres are theta at saturation and residual theta respectively

Table 25.11: *Bulk density (g cm^{-3}) and soil moisture retention data (θ in m^3 m^{-3}) for soil samples collected within the Oleolega drainage basin after logging and burning. Modelled θ values are shown in italics.*

Sample Code	Depth cm	Bd g/cm3	Theta at various soil moisture tensions (pF) **0.4**	**1.0**	**1.4**	**1.7**	**2.0**	**2.4**	**2.7**	**3.0**	**4.2**	**Air**	A.M.P. m3/m3
OSMP2	3.5	1.06	0.575	0.504	0.460	0.439	0.422	0.384	0.365	0.311	0.257	0.043	0.165
OSMP2	70.5	1.29	0.535	0.524	0.513	0.501	0.489	0.465	0.451	*0.431*	0.370	0.086	0.119
O4A	3.5	0.87	0.503	0.426	0.391	0.373	0.356	0.322	0.304	0.200	0.100	0.022	0.257
O4B	3.5	1.06	0.545	0.446	0.396	0.379	0.366	0.342	0.323	0.252	0.127	0.031	0.239
O4	41.5	1.29	0.461	0.460	0.433	0.410	0.394	0.361	0.346	0.258	0.128	0.022	0.266
O5	3.5	1.15	0.528	0.443	0.413	0.400	0.388	0.358	0.341	0.292	0.143	0.027	0.245
O5	68.5	1.48	0.464	0.459	0.457	0.452	0.437	0.408	0.390	0.322	0.100	0.024	0.338
O11	3.5	0.99	0.539	0.425	0.380	0.362	0.347	0.316	0.301	0.260	0.185	0.027	0.162
O11	46.5	1.37	0.528	0.477	0.444	0.426	0.414	0.398	0.388	0.372	0.259	0.038	0.156
O13	3.5	1.14	0.564	0.540	0.512	0.455	0.376	0.262	0.239	0.127	0.050	0.015	0.325
O13	69.5	1.26	0.530	0.510	0.452	0.414	0.382	0.321	0.294	0.189	0.093	0.021	0.289
O18	3.5	1.06	0.463	0.452	0.430	0.425	0.413	0.381	0.364	0.280	0.190	0.027	0.223
O18	44.5	1.32	0.518	0.516	0.513	0.511	0.504	0.492	0.484	0.412	0.307	0.037	0.197
O19	3.5	1.19	0.563	0.488	0.445	0.429	0.413	0.380	0.361	0.326	0.242	0.022	0.171
O19	43.5	1.33	0.461	0.459	0.435	0.419	0.403	0.375	0.361	0.344	0.258	0.021	0.145
O27	10.5	1.24	0.487	0.396	0.339	0.313	0.290	0.243	0.223	0.157	0.073	0.017	0.217
O27	60.5	1.61	0.390	0.382	0.381	0.376	0.366	0.343	0.328	0.265	0.089	0.025	0.277
O42	3.5	1.08	0.562	0.493	0.460	0.445	0.432	0.399	0.382	0.318	0.091	0.030	0.341
O42	57.5	1.46	0.515	0.512	0.512	0.503	0.488	0.467	0.454	0.422	0.287	0.032	0.201
O47	3.5	1.22	0.555	0.546	0.541	0.533	0.520	0.477	0.446	0.378	0.204	0.031	0.315
O47	45.5	1.15	0.622	0.623	0.621	0.618	0.607	0.579	0.564	0.523	0.325	0.031	0.283
O61	3.5	1.21	0.555	0.438	0.392	0.376	0.358	0.326	0.310	0.204	0.072	0.015	0.286
O61	65.5	1.76	0.316	0.308	0.302	0.295	0.284	0.264	0.253	*0.198*	0.087	0.021	0.197
O64	3.5	1.18	0.522	0.428	0.395	0.383	0.365	0.333	0.317	0.260	0.101	0.033	0.263
O64	65.5	1.59	0.435	0.433	0.430	0.428	0.419	0.404	0.394	0.333	0.157	0.031	0.261
O36A	3.5	1.25											

Bd: Bulk density, Air: Theta of air dry soil (pF between 5 and 6)
A.M.P.: Available moisture for plants (Field capacity (pF=2) minus capacity at wilting point (pF=4.2))

Table 25.12: *Measured saturated hydraulic conductivities (mm day^{-1}), model parameters and correlation coefficients (r), and modelled unsaturated hydraulic conductivities (mm day^{-1}) for soil samples collected within the Oleolega drainage basin after logging and burning.*

Sample Code	Depth cm	K-sat mm/d	Model parameters Tsat* m3/m3	Tres* m3/m3	Alpha	n	r	Modelled K-unsat pF=1 mm/d	pF=2 mm/d	pF=3 mm/d	pF=4.2 mm/d
OSMP2	3.5	2810	0.63	0.04	0.7648	1.1074	0.98	0.233	0.001	0.000	0.000
OSMP2	70.5	0.84	0.54	0.09	0.0546	1.0681	1.00	0.004	0.000	0.000	0.000
O4A	3.5	1473	0.58	0.05	1.5888	1.1127	0.96	0.541	0.003	0.000	0.000
O4B	3.5	153000	0.60	0.03	0.5575	1.4450	0.87	36.0	0.181	0.001	0.000
O4	41.5	41	0.47	0.02	0.1146	1.2449	0.93	3.7	0.250	0.001	0.000
O5	3.5	188	0.62	0.03	2.8854	1.0943	0.89	0.001	0.000	0.000	0.000
O5	68.5	5	0.47	0.02	0.0035	1.2585	0.95	1.7	0.360	0.005	0.000
O11	3.5	11945	0.68	0.03	2.5592	1.1399	0.92	0.086	0.000	0.000	0.000
O11	46.5	215	0.57	0.01	0.9159	1.0723	0.91	0.007	0.000	0.000	0.000
O13	3.5	1060	0.57	0.02	0.0249	1.3954	0.99	206	3.9	0.006	0.000
O13	69.5	240	0.53	0.02	0.0314	1.2764	0.96	21.9	0.391	0.001	0.000
O18	3.5	720	0.53	0.04	21.546	1.0353	0.93	0.000	0.000	0.000	0.000
O18	44.5	0.44	0.52	0.15	0.0025	1.2375	0.96	0.149	0.039	0.001	0.000
O19	3.5	1600	0.69	0.03	4.0791	1.0947	0.96	0.003	0.000	0.000	0.000
O19	43.5	110	0.47	0.05	0.0486	1.0996	0.98	1.09	0.021	0.000	0.000
O27	10.5	133	0.57	0.03	0.8500	1.1730	0.98	0.014	0.000	0.000	0.000
O27	60.5	2	0.39	0.03	0.0330	1.2854	0.93	0.775	0.181	0.003	0.000
O42	3.5	29500	0.64	0.05	2.3057	1.0851	0.94	0.169	0.001	0.000	0.000
O42	57.5	8.2	0.52	0.03	0.0052	1.1422	0.99	0.984	0.140	0.002	0.000
O47	3.5	213	0.60	0.04	33.673	1.0177	0.86	0.000	0.000	0.000	0.000
O47	45.5	20.3	0.63	0.03	0.0020	1.2008	0.99	6.0	1.7	0.064	0.000
O61	3.5	4430	0.64	0.02	1.2275	1.1364	0.90	0.168	0.001	0.000	0.000
O61	65.5	18	0.32	0.02	0.0046	1.3205	0.94	7.1	1.32	0.012	0.000
O64	3.5	4533	0.61	0.04	1.9979	1.1133	0.90	0.048	0.000	0.000	0.000
O64	65.5	0.91	0.44	0.03	0.0017	1.3514	0.98	0.526	0.202	0.007	0.000
O36A	3.5	0.01									

*: Tsat, Tres are theta at saturation and residual theta respectively

Table 25.13: *Bulk density (g cm^{-3}) and soil moisture retention data (θ in m^3 m^{-3}) for soil samples collected on skidder tracks, roads and landings in Oleolega drainage basin. Modelled θ values are shown in italics.*

Sample Code	Depth cm	Bd g/cm3	Theta at various soil moisture tensions (pF) **0.4**	**1.0**	**1.4**	**1.7**	**2.0**	**2.4**	**2.7**	**3.0**	**4.2**	**Air**	A.M.P. m3/m3
O5	3.5	1.05	0.572	0.566	0.556	0.550	0.538	0.490	0.461	0.263	0.163	0.022	0.375
O11	3.5	1.10	0.508	0.482	0.443	0.415	0.392	0.357	0.339	0.308	0.207	0.029	0.185
O13	3.5	1.16	0.548	0.461	0.430	0.416	0.399	0.364	0.351	0.288	0.206	0.026	0.193
O18	3.5	1.26	0.546	0.534	0.527	0.514	0.497	0.435	0.371	0.254	0.137	0.025	0.360
O19	3.5	1.15	0.564	0.472	0.423	0.405	0.387	0.347	0.327	0.252	0.135	0.023	0.251
O27	3.5	1.40	0.491	0.475	0.465	0.459	0.450	0.422	0.405	0.359	0.258	0.038	0.192
O36B	3.5	1.15											
O42	3.5	1.27	0.580	0.541	0.484	0.458	0.439	0.405	0.387	0.333	0.2	0.027	0.240
O61	3.5	1.20	0.602	0.592	0.560	0.535	0.516	0.472	0.448	0.358	0.204	0.035	0.312
O64	3.5	0.99	0.634	0.628	0.604	0.586	0.557	0.506	0.483	0.338	0.184	0.031	0.373
O73B	3.5	1.28											

Bd: Bulk density, Air: Theta of air dry soil (pF between 5 and 6)
A.M.P.: Available moisture for plants (Field capacity (pF=2) minus capacity at wilting point (pF=4.2))

Table 25.14: *Measured saturated hydraulic conductivities (mm day^{-1}), model parameters and correlation coefficients (r), and modelled unsaturated hydraulic conductivities (mm day^{-1}) for soil samples collected on skidder tracks, roads and landings in Oleolega catchment.*

Sample Code	Depth cm	K-sat mm/d	Model parameters Tsat* m3/m3	Tres* m3/m3	Alpha	n	r	Modelled K-unsat pF=1 mm/d	pF=2 mm/d	pF=3 mm/d	pF=4.2 mm/d
O5	3.5	1.6	0.57	0.02	0.0037	1.3893	0.90	0.834	0.201	0.002	0.000
O11	3.5	140	0.52	0.03	0.1045	1.1267	0.99	0.705	0.007	0.000	0.000
O13	3.5	690	0.60	0.03	0.7032	1.1128	0.94	0.073	0.000	0.000	0.000
O18	3.5	177	0.55	0.03	0.0062	1.3676	0.97	10.5	0.056	0.000	0.000
O19	3.5	43	0.61	0.02	0.3611	1.1502	0.91	0.027	0.000	0.000	0.000
O27	3.5	1.3	0.49	0.04	0.0110	1.1357	0.97	0.092	0.007	0.000	0.000
O36B	3.5	49									
O42	3.5	351	0.60	0.03	0.1321	1.1319	0.94	1.3	0.011	0.000	0.000
O61	3.5	413	0.60	0.04	0.0118	1.2138	0.96	57.5	3.8	0.023	0.000
O64	3.5	0.164	0.63	0.03	0.0063	1.2970	0.96	0.052	0.007	0.000	0.000
O73B	3.5	0.1									

*: Tsat, Tres are theta at saturation and residual theta respectively

Chapter 26

Soil Chemical Data

All data on the soil pH, pH_{KCl}, %N, %C, LOI, exchangeable cations (Na, K, Ca, Mg, NH_4), extractable P and soluble NO_3 are presented in this appendix. The analytical data for 31 bulked and single soil samples collected in Tulasewa forest are presented in Table 26.1. Analytical data on 30 bulked and single samples collected in Korokula forest and 29 samples collected in Koromani forest are given in Tables 26.2 and 26.3 respectively.

Data on the soil pH, pH_{KCl}, %N, %C, LOI, exchangeable cations (Na, K, Ca, Mg, NH_4), extractable P and soluble NO_3 for depths of 0–10 cm, 10–20 cm and 30–50 cm collected at 25 sample points in the forested Oleolega catchment in December 1990 are presented in Tables 26.4, 26.5 and 26.6 respectively. The locations of the sample points are shown by the points with corresponding numbers as shown in Figure 15.3.

The forest in the Oleolega catchment was logged and burned between December 1990 and August 15, 1991 and soil samples were collected in August–September 1991 at the same locations and depths as those collected when the catchment was still under forest. When landings or tracks were constructed at a sample point location soil samples were collected at the sample point as well as in an area near the sample point where the soil had not been disturbed by earth moving machinery or skidders. The analytical data for the relatively undisturbed samples collected at depths of 0–10 cm, 10-20 cm, 30–40 cm and 50–60 cm are shown in Tables 26.7, 26.8, 26.9 and 26.10 respectively. Exchangeable cations, soluble NO_3 and extractable PO_4 were not analysed for the samples collected at a depth of 30–40 cm. samples collected at a depth of 30–40 cm.

Analytical data obtained from samples collected at depths of 0–10 cm, 10–20 cm and between 30–60 cm on landings, roads and skidder tracks at or near 14 of the 25 sample points are given in Tables 26.11, 26.12 and 26.13 respectively. Exchangeable cations and NO_3 and extractable PO_4 were not analysed for samples collected between depths of 30–60 cm.

Table 26.1: *Analytical data obtained from soil samples collected in Tulasewa forest. The number of sample points is given by n, the LOI is in percentage of oven dry material and the exchangeable cations (Na, K, Ca, Mg and NH_4), soluble NO_3 and extractable PO_4 are given in meq 100 g^{-1} dry soil.*

Sample	Depth	n	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
AA1	0-10 cm	3	4.84	3.95	0.156	2.53	8.5	0.142	0.057	3.256	4.356	0.078	0.003	0.009
AB1		4	4.90	3.81	0.130	2.20	11.0	0.137	0.191	2.414	7.840	0.037	0.004	0.002
A32		1	5.22	4.11	0.284	3.74	5.4	0.263	0.171	2.549	9.092	0.069	0.023	0.014
A47		1	5.22	3.93	0.141	1.74	11.6	0.091	0.101	1.249	7.707	0.025	0.006	0.001
A126		1	5.16	3.94	0.144	2.26	11.0	0.146	0.160	2.695	9.167	0.053	0.001	0.006
A141		1	5.23	4.06	0.143	1.57	7.0	0.104	0.150	2.535	7.145	0.071	0.003	0.003
A221		1	5.13	4.21	0.242	3.51	11.2	0.198	0.133	3.342	5.974	0.078	0.018	0.005
Soil pit	0-8 cm	1	5.51	4.24	0.277	3.98	13.0	0.280	0.080	2.390	6.620			
Weighted Average			**5.05**	**3.97**	**0.171**	**2.55**	**9.9**	**0.158**	**0.133**	**2.630**	**6.933**	**0.057**	**0.006**	**0.005**
SD			*0.20*	*0.14*	*0.055*	*0.71*	*2.1*	*0.054*	*0.053*	*0.544*	*1.630*	*0.020*	*0.007*	*0.004*
AA2	10-20 cm	3	5.02	4.03	0.124	1.86	8.2	0.139	0.045	2.951	4.485	0.027	0.009	0.004
AB2		4	4.91	3.78	0.105	1.55	10.7	0.134	0.089	1.852	7.022	0.040	0.004	0.008
A32		1	5.42	4.14	0.177	2.00	14.4	0.200	0.092	2.509	10.677	0.041	0.008	0.001
A47		1	5.33	3.94	0.114	0.80	9.0	0.083	0.043	0.583	5.161	0.015	0.008	0.001
A126		1	5.28	3.93	0.102	1.05	10.6	0.130	0.143	2.582	10.277	0.024	0.000	0.001
A141		1	5.60	4.18	0.098	0.87	6.7	0.140	0.084	2.451	9.428	0.026	0.001	0.001
A221		1	5.30	4.19	0.150	1.76	8.7	0.189	0.102	3.201	6.713	0.036	0.021	0.001
Weighted Average			**5.14**	**3.97**	**0.119**	**1.52**	**9.7**	**0.141**	**0.080**	**2.299**	**6.983**	**0.032**	**0.007**	**0.004**
SD			*0.23*	*0.15*	*0.022*	*0.39*	*1.9*	*0.028*	*0.029*	*0.706*	*2.093*	*0.008*	*0.005*	*0.003*
AA3	20-30 cm	3	5.14	4.05	0.098	1.39	8.0	0.215	0.036	3.060	6.556	0.028	0.014	0.002
AB3		4	4.90	3.75	0.087	1.18	9.7	0.173	0.089	2.080	7.201	0.022	0.018	0.011
ABMS3		5	5.10	3.65	0.058	0.73	7.4	0.156	0.065	1.833	6.747	0.008	0.004	0.002
Soil pit	19-26 cm	1	5.22	4.16	0.188	2.37	12.1	0.290	0.060	2.240	7.750			
Weighted Average			**5.06**	**3.81**	**0.086**	**1.15**	**8.6**	**0.185**	**0.065**	**2.223**	**6.920**	**0.018**	**0.011**	**0.005**
SD			*0.11*	*0.18*	*0.034*	*0.44*	*1.4*	*0.038*	*0.019*	*0.476*	*0.346*	*0.008*	*0.006*	*0.004*
AA5	40-50 cm	3	5.39	4.02	0.045	0.54	6.2	0.306	0.059	1.748	7.702	0.009	0.004	0.001
AB5		4	5.12	3.80	0.049	0.64	8.5	0.122	0.073	0.686	5.062	0.012	0.011	0.004
ABMS5		5	5.04	3.74	0.026	0.31	6.2	0.225	0.068	1.227	7.453	0.005	0.006	0.001
Soil pit	35-40 cm	1	5.28	4.13	0.052	0.55	10.2	0.300	0.080	2.360	10.980			
Weighted Average			**5.16**	**3.85**	**0.039**	**0.48**	**7.2**	**0.218**	**0.068**	**1.268**	**7.046**	**0.008**	**0.007**	**0.002**
SD			*0.14*	*0.13*	*0.011*	*0.14*	*1.4*	*0.072*	*0.006*	*0.500*	*1.601*	*0.003*	*0.003*	*0.001*
AA7	60-70 cm	3	5.54	4.12	0.022	0.28	5.7	0.350	0.054	1.685	8.238	0.001	0.003	0.001
AB7		4	5.23	3.83	0.031	0.32	7.8	0.166	0.091	0.764	7.470	0.008	0.006	0.002
ABMS7		5	5.21	3.78	0.020	0.19	6.4	0.303	0.091	0.770	8.756	0.003	0.005	0.002
Soil pit	50-63 cm	1	5.67	4.16	0.029	0.23	9.4	0.380	0.080	2.010	10.740			
Weighted Average			**5.33**	**3.90**	**0.025**	**0.25**	**6.9**	**0.278**	**0.082**	**1.075**	**8.393**	**0.004**	**0.005**	**0.002**
SD			*0.17*	*0.15*	*0.005*	*0.06*	*1.1*	*0.078*	*0.015*	*0.468*	*0.861*	*0.003*	*0.001*	*0.000*
AA10	90-100 cm	3	5.71	4.11	0.012	0.09	5.4	0.429	0.063	1.397	10.190	0.001	0.005	0.002
AB10		4	5.20	3.55	0.020	0.17	7.5	0.243	0.110	1.304	8.836	0.009	0.005	0.002
Soil pit	75-80 cm	1	5.45	4.22	0.023	0.20		0.420	0.080	1.830	10.690			
Weighted Average			**5.42**	**4.39**	**0.017**	**0.14**	**6.6**	**0.335**	**0.089**	**1.405**	**9.576**	**0.006**	**0.005**	**0.002**
SD			*0.24*	*0.30*	*0.004*	*0.04*	*1.0*	*0.092*	*0.022*	*0.166*	*0.755*	*0.004*	*0.000*	*0.000*
Soil pit	115-130 cm	1	5.58	4.13		0.01		0.360	0.110	2.060	11.960			

pH*: pH of soil in KCl solution

Table 26.2: *Analytical data obtained from soil samples collected in Korokula forest. The number of sample points is given by n, the LOI is in percentage of oven dry material and the exchangeable cations (Na, K, Ca, Mg and NH_4), soluble NO_3 and extractable PO_4 are given in meq 100 g^{-1} dry soil.*

Sample	Depth	n	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
BA1	0-10 cm	4	5.36	4.23	0.117	1.86	6.6	0.168	0.042	2.263	2.813	0.050	0.006	0.007
BB1		3	5.45	4.44	0.171	2.66	6.8	0.220	0.063	1.999	4.582	0.071	0.036	0.016
B17		1	5.54	4.42	0.106	1.51	7.1	0.210	0.097	3.019	3.797	0.069	0.104	0.009
B32		1	5.34	4.46	0.157	2.30	7.3	0.234	0.084	2.789	3.823	0.076	0.014	0.007
B59		1	5.39	4.49	0.234	3.76	6.2	0.339	0.082	2.939	4.663	0.052	0.046	0.011
B80		1	5.41	4.45	0.169	2.58	7.5	0.339	0.084	2.953	4.047	0.040	0.035	0.016
B92		1	5.63	4.31	0.077	0.88	5.2	0.262	0.059	1.942	3.080	0.026	0.008	0.003
Soil pit	0-10 cm	1	5.67	4.36	0.127	2.09	5.6	0.034	0.030	1.370	1.230			
Weighted Average			**5.44**	**4.36**	**0.142**	**2.20**	**6.6**	**0.212**	**0.061**	**2.312**	**3.511**	**0.056**	**0.028**	**0.010**
SD			*0.10*	*0.10*	*0.039*	*0.67*	*0.6*	*0.076*	*0.020*	*0.469*	*0.983*	*0.015*	*0.027*	*0.004*
BA2	10-20 cm	4	5.38	4.15	0.104	1.71	5.7	0.197	0.025	2.230	3.546	0.025	0.006	0.003
BB2		3	5.35	4.40	0.147	2.20	6.0	0.220	0.063	1.999	4.582	0.071	0.036	0.010
B17		1	5.83	4.37	0.085	1.04	5.2	0.240	0.035	2.792	3.607	0.040	0.035	0.003
B32		1	5.55	4.45	0.137	1.82	6.3	0.181	0.050	2.251	3.333	0.051	0.049	0.002
B59		1	5.59	4.34	0.130	1.73	9.1	0.332	0.035	2.496	4.711	0.030	0.020	0.001
B80		1	5.71	4.51	0.102	1.26	7.0	0.233	0.034	2.645	3.553	0.025	0.006	0.002
B92		1	5.83	4.38	0.100	1.34	5.5	0.271	0.056	1.939	3.515	0.024	0.015	0.001
Weighted Average			**5.51**	**4.32**	**0.118**	**1.72**	**6.2**	**0.225**	**0.042**	**2.253**	**3.887**	**0.040**	**0.021**	**0.004**
SD			*0.18*	*0.13*	*0.021*	*0.36*	*1.0*	*0.040*	*0.016*	*0.258*	*0.519*	*0.019*	*0.015*	*0.003*
BA3	20-30 cm	4	5.50	4.15	0.074	1.17	5.6	0.195	0.019	1.735	4.076	0.022	0.003	0.005
BB3		3	5.45	4.32	0.100	1.61	4.9	0.145	0.020	1.070	2.563	0.023	0.005	0.005
Soil pit	18-35 cm	1	6.01	4.35	0.033	0.46	3.2	0.350	0.020	0.980	1.130			
Weighted Average			**5.55**	**4.24**	**0.079**	**1.25**	**5.0**	**0.196**	**0.020**	**1.391**	**3.140**	**0.022**	**0.004**	**0.005**
SD			*0.18*	*0.09*	*0.021*	*0.36*	*0.8*	*0.063*	*0.001*	*0.345*	*1.033*	*0.006*	*0.010*	*0.001*
BA5	40-50 cm	4	5.66	4.08	0.029	0.41	4.4	0.217	0.025	0.831	7.117	0.002	0.003	0.005
BB5		3	5.63	4.38	0.034	0.45	3.6	0.165	0.024	0.661	3.539	0.003	0.005	0.001
BBMS5		5	5.40	4.00	0.054	0.80	5.2	0.244	0.036	1.400	5.161	0.007	0.011	0.002
Soil pit		1	5.92	4.66	0.039	0.36	7.0	0.420	0.070	1.180	8.220			
Weighted Average			**5.57**	**4.16**	**0.041**	**0.57**	**4.7**	**0.231**	**0.032**	**1.037**	**5.624**	**0.004**	**0.007**	**0.003**
SD			*0.15*	*0.21*	*0.011*	*0.19*	*0.9*	*0.062*	*0.012*	*0.313*	*1.513*	*0.002*	*0.004*	*0.002*
BA7	60-70 cm	4	5.79	4.00	0.019	0.36	4.4	0.336	0.024	0.017	9.506	0.001	0.005	0.002
BB7		3	5.70	4.44	0.028	0.33	4.4	0.317	0.026	0.443	3.964	0.001	0.005	0.002
BBMS7		5	5.66	4.18	0.022	0.28	4.9	0.327	0.030	0.917	7.744	0.001	0.009	0.001
Soil pit		1	6.65	4.47	0.020	0.20	7.4	0.510	0.060	1.360	15.170			
Weighted Average			**5.79**	**4.21**	**0.022**	**0.31**	**4.8**	**0.342**	**0.030**	**0.565**	**7.985**	**0.001**	**0.007**	**0.002**
SD			*0.26*	*0.18*	*0.003*	*0.05*	*0.8*	*0.049*	*0.009*	*0.438*	*2.905*	*0.000*	*0.002*	*0.000*
BA9	80-90 cm	2	5.95	4.09	0.015	0.17	4.4	0.228	0.027	0.051	7.731	0.001	0.006	0.001
BB9		2	5.95	4.65	0.030	0.34	5.2	0.424	0.017	0.312	7.170	0.001	0.004	0.005
Soil pit		1	6.54	4.12		0.06	7.4	0.530	0.040	1.160	16.640			
Weighted Average			**6.07**	**4.32**	**0.023**	**0.22**	**5.3**	**0.339**	**0.025**	**0.288**	**8.634**	**0.001**	**0.005**	**0.003**
SD			*0.24*	*0.27*	*0.008*	*0.11*	*1.1*	*0.120*	*0.008*	*0.408*	*3.684*	*0.000*	*0.001*	*0.002*
BB11	100-110 cm	1	5.92	4.68	0.042	0.59	7.0	0.593	0.011	0.322	10.032	0.001	0.003	0.002

pH*: pH of soil in KCl solution

Table 26.3: *Analytical data obtained from soil samples collected in Koromani forest. The number of sample points is given by n, the LOI is in percentage of oven dry material and the exchangeable cations (Na, K, Ca, Mg and NH_4), soluble NO_3 and extractable PO_4 are given in meq 100 g^{-1} dry soil.*

Sample	Depth	n	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
CR1	0-10 cm	3	4.83	3.78	0.160	3.43	13.0	0.145	0.054	2.023	2.187	0.045	0.006	0.012
CM1		3	4.35	3.85	0.191	3.57	14.0	0.152	0.039	2.043	2.253	0.058	0.008	0.014
CV1		3	4.52	3.98	0.217	3.58	14.3	0.281	0.064	2.608	2.459	0.069	0.023	0.016
C20		1	5.10	4.29	0.178	3.64	14.3	0.177	0.062	3.178	2.045	0.052	0.010	0.008
C88		1	5.17	4.36	0.232	4.05	15.3	0.220	0.076	3.568	2.806	0.107	0.089	0.008
C98		1	5.17	4.40	0.138	2.58	14.0	0.172	0.049	1.950	1.402	0.051	0.011	0.001
Soil pit		1	4.99	4.33	0.191	3.07	15.1	0.200	0.030	1.580	1.470			
Weighted Average			**4.73**	**4.02**	**0.188**	**3.47**	**14.0**	**0.193**	**0.053**	**2.331**	**2.186**	**0.061**	**0.018**	**0.012**
SD			*0.30*	*0.23*	*0.027*	*0.33*	*0.7*	*0.053*	*0.013*	*0.535*	*0.369*	*0.017*	*0.022*	*0.004*
CR2	10-20 cm	3	5.02	3.72	0.082	1.49	10.1	0.060	0.020	0.688	0.941	0.014	0.004	0.005
CM2		3	4.45	3.84	0.124	2.31	12.1	0.088	0.019	1.129	1.417	0.031	0.008	0.005
CV2		3	4.57	3.94	0.142	2.23	12.2	0.115	0.022	1.296	1.420	0.037	0.010	0.003
C20		1	5.10	4.00	0.073	1.00	10.4	0.144	0.027	1.502	1.250	0.016	0.009	0.003
C88		1	5.14	4.18	0.169	2.74	12.8	0.116	0.038	1.833	1.723	0.042	0.031	0.001
C98		1	5.17	4.40	0.065	0.82	14.0	0.106	0.029	1.159	1.128	0.024	0.010	0.001
SoilPit	14-20 cm	1	5.21	4.24	0.091	1.62	11.3	0.270	0.020	1.190	1.190			
Weighted Average			**4.83**	**3.95**	**0.111**	**1.87**	**11.7**	**0.110**	**0.023**	**1.156**	**1.279**	**0.027**	**0.010**	**0.004**
SD			*0.30*	*0.20*	*0.032*	*0.56*	*1.2*	*0.053*	*0.005*	*0.316*	*0.230*	*0.010*	*0.007*	*0.001*
CR3	20-30 cm	3	4.90	3.71	0.061	1.13	9.6	0.061	0.018	0.431	0.718	0.009	0.004	0.003
CM3		3	4.43	3.84	0.093	1.67	11.1	0.077	0.013	0.857	1.269	0.020	0.006	0.003
CV3		3	4.52	3.91	0.093	1.46	7.4	0.069	0.011	0.969	1.007	0.017	0.013	0.002
CBMS3		3	5.48	4.00	0.074	1.22	10.2	0.075	0.019	0.810	0.774	0.011	0.007	0.002
Weighted Average			**4.83**	**3.87**	**0.080**	**1.37**	**9.6**	**0.071**	**0.015**	**0.767**	**0.942**	**0.014**	**0.008**	**0.003**
SD			*0.41*	*0.11*	*0.014*	*0.21*	*1.4*	*0.006*	*0.003*	*0.202*	*0.218*	*0.004*	*0.003*	*0.001*
CR5	40-50 cm	3	4.95	3.59	0.034	0.47	8.7	0.035	0.017	0.023	0.138	0.006	0.004	0.003
CM5		3	4.70	3.85	0.065	0.84	10.0	0.070	0.007	0.327	0.753	0.009	0.010	0.002
CV5		3	4.40	3.93	0.068	0.73	9.5	0.055	0.006	0.270	0.511	0.009	0.013	0.005
CBMS5		3	5.05	3.80	0.038	0.55	8.7	0.080	0.019	0.170	0.209	0.007	0.004	0.003
SoilPit	43-53 cm	1	4.98	4.17	0.059	0.64	11.7	0.290	0.020	0.650	0.730			
Weighted Average			**4.79**	**3.82**	**0.052**	**0.65**	**9.4**	**0.078**	**0.013**	**0.232**	**0.428**	**0.008**	**0.008**	**0.003**
SD			*0.25*	*0.16*	*0.015*	*0.14*	*0.8*	*0.063*	*0.006*	*0.164*	*0.252*	*0.001*	*0.004*	*0.001*
CR7	60-70 cm	3	4.56	3.66	0.026	0.41	8.1	0.031	0.025	0.017	0.094	0.004	0.003	0.002
CM7		3	4.62	3.82	0.052	0.60	10.5	0.064	0.006	0.086	0.281	0.007	0.009	0.002
CV7		3	4.40	3.94	0.049	0.56	9.5	0.072	0.010	0.245	0.498	0.007	0.012	0.002
CBMS7		3						0.042	0.018	0.191	0.338	0.007	0.003	0.001
SoilPit	73-93 cm	1	5.21	4.09	0.030	0.33	10.8	0.320	0.020	0.600	0.800			
Weighted Average			**4.60**	**3.84**	**0.041**	**0.50**	**9.5**	**0.076**	**0.014**	**0.153**	**0.330**	**0.006**	**0.008**	**0.002**
SD			*0.22*	*0.14*	*0.012*	*0.10*	*1.0*	*0.073*	*0.007*	*0.151*	*0.192*	*0.001*	*0.004*	*0.000*
Soil pit	97-105 cm	1	4.68	4.05		0.19		0.290	0.020	0.600	0.630			
Soil pit	152-162 cm	1	4.46	4.01		0.11		0.310	0.020	0.560	0.540			

pH*: pH of soil in KCl solution

Table 26.4: *Analytical data obtained from 25 soil samples collected at a depth of 0–10 cm in the forested Oleolega catchment. The LOI is in percentage of oven dry material and the exchangeable cations (Na, K, Ca, Mg and NH_4), soluble NO_3 and extractable PO_4 are given in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	4.04	3.53	0.242	3.369	9.1	0.159	0.046	0.771	0.823	0.120	0.049	0.038
5	3.97	3.54	0.091	1.312	6.7	0.105	0.099	0.550	0.904	0.066	0.007	0.002
8	4.34	3.90	0.078	1.558	7.0	0.106	0.150	0.094	0.493	0.091	0.012	0.001
9	4.29	4.01	0.286	3.829	10.0	0.151	0.148	1.683	2.030	0.121	0.746	0.040
11	4.12	3.73	0.110	2.379	7.2	0.107	0.038	0.066	0.429	0.130	0.045	0.005
13	5.04	4.40	0.067	0.948	4.0	0.176	0.105	0.735	1.614	0.059	0.091	0.007
14	5.34	5.11	0.460	5.584	12.6	0.337	0.213	4.834	3.366	0.152	0.132	0.112
18	4.83	4.41	0.096	1.539	9.7	0.180	0.062	1.698	1.031	0.080	0.084	0.001
19	4.74	4.21	0.141	1.953	8.1	0.231	0.116	1.558	1.129	0.101	0.122	0.014
22	4.51	3.68	0.077	1.794	7.4	0.340	0.027	0.212	2.050	0.056	0.056	0.012
24	4.06	3.48	0.081	1.585	8.1	0.134	0.076	0.492	0.775	0.106	0.010	0.001
27	4.36	3.67	0.078	2.216	6.0	0.203	0.046	0.785	0.964	0.066	0.013	0.014
34	4.32	3.78	0.123	2.255	8.3	0.130	0.055	1.025	1.332	0.101	0.053	0.007
36	4.69	4.07	0.115	2.020	7.3	0.183	0.033	0.985	2.735	0.107	0.088	0.011
33	5.01	3.60	0.235	3.201	10.4	0.162	0.306	2.890	2.696	0.155	0.525	0.026
42	5.04	4.61	0.169	2.826	12.6	0.129	0.082	2.299	1.700	0.142	0.137	0.002
45	4.73	3.89	0.085	1.527	7.5	0.170	0.162	0.740	4.936	0.199	0.129	0.002
47	4.55	3.98	0.084	1.676	9.5	0.217	0.255	0.398	1.736	0.335	0.008	0.002
54	4.02	3.14	0.076	1.348	8.1	0.116	0.122	0.893	0.689	0.281	0.032	0.002
59	4.35	3.61	0.192	3.002	10.1	0.154	0.206	1.573	3.846	0.438	0.060	0.006
60	4.70	3.90	0.069	1.913	8.3	0.095	0.109	0.593	0.818	0.175	0.002	0.003
61	4.73	4.01	0.055	1.280	6.2	0.096	0.161	0.954	1.137	0.306	0.191	0.006
64	5.15	4.34	0.118	2.039	6.0	0.206	0.076	3.414	6.585	0.287	0.143	0.008
67	4.82	4.12	0.161	2.446	12.0	0.205	0.078	1.876	1.709	0.340	0.152	0.002
73	5.33	4.65	0.113	1.930	6.0	0.147	0.085	0.895	2.653	0.246	0.341	0.004
Average	**4.60**	**3.97**	**0.136**	**2.221**	**8.3**	**0.170**	**0.114**	**1.280**	**1.927**	**0.170**	**0.129**	**0.013**
SD	**0.40**	**0.43**	**0.089**	**0.978**	**2.1**	**0.063**	**0.070**	**1.091**	**1.450**	**0.103**	**0.170**	**0.023**

* pH measured in KCl solution

Table 26.5: *Analytical data obtained from 25 soil samples collected at a depth of 10–20 cm in the forested Oleolega catchment. The LOI is in percentage of oven dry material and the exchangeable cations (Na, K, Ca, Mg and NH_4), soluble NO_3 and extractable PO_4 are given in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	4.30	3.81	0.169	2.154	7.5	0.136	0.025	0.443	0.500	0.062	0.042	0.016
5	4.01	3.57	0.051	0.703	6.2	0.082	0.134	0.191	0.454	0.102	0.005	0.001
8	4.16	3.77	0.028	0.313	4.3	0.062	0.082	0.017	0.088	0.092	0.020	0.001
9	4.07	3.69	0.149	1.569	7.7	0.115	0.127	0.321	1.296	0.082	0.251	0.010
11	4.19	3.78	0.093	2.029	6.5	0.192	0.030	0.034	0.450	0.115	0.039	0.006
13	4.98	4.22	0.062	0.765	3.7	0.101	0.093	0.768	1.803	0.069	0.110	0.004
14	5.06	4.48	0.162	1.637	6.9	0.131	0.065	1.403	1.561	0.067	0.145	0.011
18	4.66	4.12	0.077	1.053	9.7	0.087	0.046	1.499	0.932	0.060	0.047	0.001
19	4.78	4.15	0.105	1.308	7.5	0.165	0.079	1.049	0.737	0.066	0.075	0.008
22	4.80	3.60	0.034	0.543	4.8	0.290	0.014	0.023	1.694	0.049	0.016	0.001
24	3.92	3.37	0.052	1.063	6.2	0.099	0.059	0.147	0.502	0.087	0.013	0.001
27	4.43	3.72	0.052	1.102	4.9	0.118	0.024	0.383	0.550	0.077	0.045	0.002
34	4.24	3.70	0.097	1.591	7.5	0.092	0.040	0.903	1.167	0.109	0.050	0.004
36	4.77	4.21	0.134	2.315	7.8	0.114	0.036	1.024	2.764	0.108	0.205	0.014
33	4.46	3.94	0.131	1.613	8.5	0.069	0.190	0.610	1.936	0.139	0.134	0.004
42	5.01	4.57	0.131	2.082	12.0	0.052	0.048	2.242	1.450	0.324	0.238	0.001
45	4.95	3.91	0.058	0.929	7.5	0.204	0.166	0.370	6.883	0.174	0.057	0.001
47	4.56	3.71	0.058	1.250	8.1	0.150	0.108	0.157	1.598	0.170	0.006	0.002
54	4.14	3.11	0.040	0.581	7.0	0.060	0.089	0.496	0.324	0.214	0.014	0.001
59	3.91	3.15	0.062	0.734	7.7	0.084	0.108	0.212	1.934	0.175	0.002	0.001
60	4.64	3.73	0.038	0.940	7.7	0.061	0.065	0.256	0.586	0.106	0.001	0.001
61	4.55	3.70	0.012	0.261	4.3	0.060	0.185	0.476	0.622	0.085	0.042	0.001
64	5.17	4.19	0.117	1.840	6.4	0.199	0.074	3.198	6.544	0.179	0.046	0.005
67	4.79	4.09	0.136	1.955	12.0	0.150	0.055	2.070	2.212	0.411	0.039	0.001
73	5.38	4.41	0.064	0.941	5.0	0.088	0.085	0.521	3.247	0.194	0.051	0.001
Average	**4.56**	**3.87**	**0.084**	**1.251**	**7.1**	**0.118**	**0.081**	**0.752**	**1.673**	**0.133**	**0.068**	**0.004**
SD	**0.40**	**0.37**	**0.044**	**0.586**	**2.0**	**0.056**	**0.048**	**0.776**	**1.679**	**0.084**	**0.071**	**0.004**

* pH measured in KCl solution

Table 26.6: *Analytical data obtained from soil samples (30–60 cm) collected in the forested Oleolega catchment. LOI in % of oven dry material, exchangeable Na, K, Ca, Mg, NH_4, NO_3 and Ca-Lactate extractable P in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	4.84	4.08	0.049	0.258	4.8	0.161	0.017	0.017	0.541	0.035	0.012	0.005
5	4.20	3.67	0.017	0.101	5.0	0.080	0.061	0.016	0.103	0.022	0.010	0.001
8	4.43	3.95	0.012	0.049	4.3	0.034	0.075	0.018	0.029	0.023	0.004	0.001
9	4.70	3.76	0.040	0.270	4.5	0.076	0.154	0.017	3.193	0.063	0.091	0.001
11	4.63	3.89	0.038	0.408	5.0	0.114	0.013	0.017	0.265	0.039	0.011	0.001
13	4.68	3.84	0.064	0.704	4.6	0.181	0.068	0.495	1.809	0.106	0.057	0.001
14	4.95	4.03	0.077	0.712	5.3	0.157	0.043	0.977	1.817	0.110	0.057	0.002
18	4.54	3.98	0.028	0.202	10.8	0.060	0.025	0.249	0.203	0.039	0.042	0.001
19	4.90	4.87	0.018	0.224	4.8	0.132	0.062	0.883	1.241	0.067	0.022	0.001
22	4.91	3.56	0.024	0.284	4.8	0.342	0.020	0.016	2.242	0.041	0.012	0.001
24	4.20	3.71	0.025	0.430	6.9	0.072	0.044	0.016	0.079	0.067	0.015	0.001
27	4.98	3.44	0.020	0.198	4.0	0.257	0.041	0.017	2.876	0.028	0.009	0.001
34	4.20	3.67	0.049	0.788	6.8	0.084	0.020	0.035	0.167	0.061	0.011	0.001
36	4.79	3.91	0.050	0.961	5.8	0.112	0.012	0.715	2.501	0.140	0.025	0.001
33	4.47	3.87	0.042	0.418	7.6	0.054	0.026	0.212	0.645	0.144	0.030	0.001
42	4.54	3.93	0.061	1.200	10.3	0.050	0.012	1.074	0.612	0.204	0.087	0.001
45	5.66	4.04	0.024	0.087	7.1	0.289	0.202	0.029	14.336	0.012	0.016	0.001
47	4.53	3.47	0.008	0.089	6.1	0.082	0.093	0.016	1.231	0.043	0.003	0.001
54	4.68	3.62	0.011	0.123	3.8	0.037	0.068	0.118	0.028	0.031	0.006	0.001
59	4.30	3.36	0.024	0.219	5.6	0.078	0.089	0.016	0.885	0.108	0.001	0.001
60	4.77	3.80	0.020	0.260	8.5	0.076	0.064	0.016	0.737	0.083	0.018	0.001
61	4.53	3.56	0.004	0.115	4.5	0.063	0.165	0.072	0.133	0.022	0.015	0.002
64	5.34	3.96	0.036	0.522	4.2	0.198	0.092	1.696	6.144	0.093	0.016	0.001
67	4.72	3.77	0.045	0.414	10.8	0.149	0.022	0.414	0.932	0.119	0.038	0.001
73	5.49	3.96	0.033	0.256	8.3	0.229	0.060	0.038	8.809	0.044	0.029	0.001
Average	**4.72**	**3.83**	**0.033**	**0.372**	**6.2**	**0.127**	**0.062**	**0.288**	**2.062**	**0.070**	**0.025**	**0.001**
SD	**0.37**	**0.29**	**0.018**	**0.289**	**2.1**	**0.081**	**0.049**	**0.436**	**3.209**	**0.047**	**0.024**	**0.001**

* pH measured in KCl solution

Table 26.7: *Analytical data obtained from soil samples (0–10 cm) collected in the logged and burned Oleolega catchment. LOI in % of oven dry material, exchangeable Na, K, Ca, Mg and NH_4, NO_3 and Ca-Lactate extractable P in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	5.07	4.03	0.132	2.918	8.5	0.128	0.094	1.645	1.297	0.096	0.016	0.024
5	5.15	4.21	0.094	1.862	7.7	0.095	0.188	1.030	1.083	0.123	0.008	0.005
8	4.90	3.93	0.070	1.341	6.7	0.121	0.181	0.523	0.863	0.209	0.040	0.002
9	5.07	4.43	0.308	3.534	11.0	0.093	0.278	2.747	3.548	0.180	0.312	0.036
11	5.44	4.23	0.084	1.554	7.9	0.127	0.192	1.798	2.904	0.066	0.059	0.010
13	5.54	4.84	0.070	0.975	3.9	0.077	0.253	1.512	2.852	0.031	0.079	0.004
14	5.73	4.99	0.338	4.444	10.9	0.142	0.254	4.790	4.313	0.142	0.058	0.027
18	5.36	4.45	0.163	2.651	11.0	0.097	0.126	2.651	1.912	0.094	0.063	0.007
19	5.14	4.09	0.139	1.915	8.8	0.081	0.138	1.449	1.533	0.090	0.062	0.007
22	5.37	3.96	0.079	1.867	6.3	0.108	0.084	0.810	3.173	0.050	0.015	0.010
24	5.23	4.08	0.080	1.746	7.4	0.112	0.131	0.935	1.140	0.113	0.009	0.005
27	5.21	3.98	0.068	1.574	5.9	0.099	0.059	0.752	1.013	0.085	0.019	0.016
34	5.11	4.03	0.171	3.074	9.8	0.117	0.198	1.826	2.062	0.127	0.050	0.027
36	5.39	4.60	0.206	3.157	10.0	0.067	0.319	3.064	4.166	0.151	0.011	0.021
33	5.43	4.53	0.191	2.721	10.3	0.080	0.267	2.244	2.602	0.182	0.049	0.018
42	5.35	4.55	0.167	2.655	12.8	0.084	0.069	2.754	2.395	0.105	0.034	0.005
45	5.44	4.24	0.092	2.049	8.8	0.154	0.273	1.350	5.081	0.094	0.042	0.015
47	4.87	3.73	0.012	1.184	10.3	0.097	0.049	0.041	0.503	0.027	0.004	0.001
54	4.90	3.79	0.055	0.546	8.3	0.083	0.149	0.843	0.682	0.068	0.021	0.004
59	4.91	3.92	0.155	2.074	9.2	0.133	0.193	1.019	3.097	0.082	0.004	0.009
60	5.13	3.93	0.082	1.626	8.5	0.119	0.299	0.951	1.543	0.104	0.004	0.009
61	5.22	4.15	0.060	0.990	6.3	0.059	0.249	1.400	1.599	0.065	0.050	0.014
64	5.59	4.57	0.131	2.242	6.7	0.226	0.077	2.612	6.050	0.051	0.008	0.009
67	5.35	4.65	0.216	3.297	13.6	0.141	0.270	3.545	3.308	0.140	0.022	0.004
73	5.29	4.57	0.074	2.146	7.0	0.125	0.096	1.017	2.126	0.106	0.005	0.002
Average	**5.25**	**4.26**	**0.130**	**2.166**	**8.7**	**0.111**	**0.179**	**1.732**	**2.434**	**0.103**	**0.042**	**0.012**
SD	**0.22**	**0.33**	**0.077**	**0.895**	**2.2**	**0.034**	**0.083**	**1.067**	**1.399**	**0.045**	**0.060**	**0.009**

* pH measured in KCl solution

Table 26.8: *Analytical data obtained from soil samples (10–20 cm) collected in the logged and burned Oleolega catchment. LOI in % of oven dry material, exchangeable Na, K, Ca, Mg, NH_4, NO_3 and Ca-Lactate extractable P given in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	5.13	3.96	0.095	1.908	6.7	0.123	0.068	1.255	1.098	0.118	0.008	0.007
5	4.81	4.14	0.063	1.238	7.5	0.129	0.168	0.975	1.277	0.109	0.035	0.002
8	4.91	3.87	0.040	0.771	5.7	0.115	0.154	0.314	0.542	0.150	0.028	0.001
9	4.88	3.95	0.165	1.745	8.2	0.073	0.191	1.233	2.707	0.060	0.137	0.003
11	5.30	4.13	0.076	1.316	7.6	0.094	0.106	1.296	2.488	0.042	0.032	0.002
13	5.72	4.55	0.057	0.867	3.6	0.077	0.160	1.137	2.297	0.024	0.048	0.001
14	5.69	4.70	0.161	1.708	7.2	0.130	0.115	2.723	3.407	0.079	0.034	0.003
18	5.24	4.26	0.115	1.567	9.8	0.086	0.128	2.431	2.102	0.064	0.044	0.001
19	5.04	4.00	0.088	1.235	7.9	0.058	0.099	0.974	1.090	0.056	0.040	0.001
22	5.69	3.96	0.036	0.712	4.6	0.129	0.030	0.264	3.430	0.024	0.013	0.001
24	4.00	3.87	0.049	0.771	6.3	0.058	0.086	0.176	0.614	0.052	0.004	0.001
27	5.12	4.04	0.041	0.901	4.7	0.093	0.046	0.484	0.873	0.034	0.018	0.005
34	4.90	3.92	0.101	1.995	8.2	0.107	0.131	1.341	1.683	0.081	0.045	0.009
36	5.40	4.33	0.123	1.983	10.3	0.076	0.105	2.173	2.906	0.087	0.002	0.006
33	4.86	3.90	0.106	1.431	8.5	0.072	0.119	0.589	1.770	0.077	0.025	0.003
42	5.44	4.58	0.113	2.029	11.9	0.073	0.042	2.493	1.920	0.067	0.018	0.002
45	5.53	4.06	0.061	1.075	7.8	0.168	0.205	0.553	6.745	0.054	0.023	0.006
47	4.71	3.76	0.002	0.123	10.2	0.073	0.033	0.016	0.201	0.022	0.004	0.001
54	4.96	3.83	0.034	0.497	8.1	0.064	0.130	0.457	0.429	0.040	0.012	0.001
59	4.96	3.82	0.090	1.067	8.2	0.135	0.175	0.623	3.140	0.068	0.004	0.002
60	5.17	3.95	0.049	0.992	8.0	0.088	0.228	0.491	1.153	0.050	0.003	0.002
61	5.22	4.04	0.006	0.424	4.7	0.042	0.193	0.795	1.051	0.058	0.019	0.002
64	5.76	4.44	0.119	1.830	6.5	0.249	0.075	3.048	7.240	0.033	0.002	0.003
67	5.25	4.40	0.098	1.941	11.5	0.122	0.149	2.532	2.634	0.121	0.014	0.002
73	5.37	4.57	0.050	1.251	5.3	0.092	0.068	0.682	2.293	0.054	0.006	0.001
Average	**5.16**	**4.12**	**0.077**	**1.255**	**7.6**	**0.101**	**0.120**	**1.162**	**2.204**	**0.065**	**0.025**	**0.003**
SD	**0.38**	**0.27**	**0.042**	**0.537**	**2.1**	**0.042**	**0.055**	**0.871**	**1.690**	**0.032**	**0.027**	**0.002**

* pH measured in KCl solution

Table 26.9: *Analytical data obtained from soil samples (30–40 cm) collected in the logged and burned Oleolega catchment. LOI in % of oven dry material.*

Sample pt.	pH	pH*	%N	%C	LOI
4	4.55	3.92	0.032	0.450	4.9
5	4.40	3.97	0.024	0.280	5.8
8	4.15	3.97	0.010	0.150	5.0
9	4.56	3.99	0.080	0.830	6.7
11	5.17	4.08	0.033	0.271	7.6
13	4.83	4.00	0.061	0.720	4.6
14	5.03	3.05	0.092	0.920	5.6
18	4.69	3.94	0.041	0.350	9.4
19	4.70	3.95	0.047	0.580	6.3
22	5.40	3.90	0.011	0.130	3.4
24	5.13	3.97	0.034	0.650	6.3
27	5.20	3.89	0.019	0.290	3.7
34	4.32	3.88	0.080	1.200	7.2
36	4.90	3.92	0.064	0.840	9.0
33	4.40	3.86	0.067	0.800	8.0
42	4.59	4.00	0.068	1.240	10.6
45	5.04	3.95	0.021	0.340	6.7
47	4.67	3.92	0.000	0.050	9.8
54	4.40	3.89	0.013	0.240	6.2
59	4.50	3.94	0.029	0.320	5.1
60	4.87	3.90	0.022	0.410	8.1
61	4.40	3.87	0.005	0.090	3.8
64	5.09	4.07	0.055	0.960	4.2
67	4.55	3.97	0.060	0.700	11.4
73	5.01	4.27	0.046	0.810	4.9
Average	**4.74**	**3.92**	**0.041**	**0.545**	**6.6**
SD	**0.32**	**0.20**	**0.025**	**0.337**	**2.2**

* pH measured in KCl solution

Table 26.10: *Analytical data obtained from soil samples (50–60 cm) collected in the logged and burned Oleolega catchment. LOI in % of oven dry material, exchangeable Na, K, Ca, Mg NH_4, NO_3 and Ca-Lactate extractable P in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	5.29	4.01	0.016	0.187	4.7	0.143	0.058	0.555	1.142	0.018	0.037	0.001
5	4.87	4.07	0.014	0.098	5.3	0.040	0.041	0.016	0.164	0.012	0.011	0.001
8	4.86	3.95	0.009	0.093	4.7	0.046	0.066	0.017	0.028	0.007	0.010	0.001
9	5.28	4.16	0.047	0.473	5.9	0.059	0.225	0.043	4.365	0.011	0.082	0.001
11	5.17	4.08	0.033	0.271	7.6	0.099	0.019	0.145	2.024	0.007	0.045	0.002
13	5.55	5.28	0.056	0.600	4.6	0.127	0.137	0.661	3.667	0.032	0.088	0.002
14	6.16	4.53	0.043	0.448	4.8	0.119	0.051	1.654	3.575	0.049	0.034	0.001
18	5.17	4.10	0.035	0.275	9.5	0.077	0.040	0.869	1.090	0.013	0.055	0.001
19	4.85	3.95	0.036	0.393	7.7	0.073	0.019	0.505	0.733	0.013	0.023	0.001
22	6.25	4.07	0.015	0.101	4.1	0.252	0.025	0.018	9.530	0.000	0.007	0.001
24	5.01	3.97	0.012	0.079	5.2	0.071	0.046	0.016	1.258	0.008	0.006	0.001
27	6.01	3.91	0.011	0.159	4.2	0.277	0.022	0.017	4.781	0.003	0.013	0.001
34	4.87	3.97	0.044	0.812	7.1	0.093	0.020	0.068	0.221	0.009	0.025	0.004
36	5.40	4.06	0.040	0.622	8.0	0.063	0.031	0.795	1.962	0.010	0.009	0.003
33	4.69	3.94	0.045	0.598	7.5	0.065	0.052	0.235	0.962	0.025	0.036	0.008
42	5.15	4.18	0.041	0.909	10.4	0.050	0.013	0.742	0.455	0.012	0.018	0.001
45	5.07	3.79	0.029	0.142	6.8	0.269	0.072	0.017	13.083	0.000	0.012	0.001
47	4.69	3.75	0.001	0.129	10.5	0.074	0.031	0.016	0.272	0.006	0.004	0.005
54	5.03	3.87	0.007	0.125	5.6	0.059	0.039	0.128	0.061	0.015	0.009	0.001
59	5.00	3.80	0.028	0.192	4.7	0.069	0.072	0.017	1.027	0.003	0.004	0.001
60	5.24	3.96	0.016	0.148	8.8	0.057	0.032	0.015	0.624	0.010	0.011	0.001
61	4.91	3.97	0.033	0.062	4.3	0.020	0.094	0.038	0.136	0.005	0.014	0.001
64	6.28	4.36	0.033	0.387	4.5	0.208	0.051	1.184	6.027	0.002	0.008	0.001
67	5.11	4.01	0.028	0.289	10.7	0.128	0.020	0.217	0.632	0.008	0.023	0.001
73	5.81	4.71	0.025	0.264	4.3	0.091	0.025	0.018	3.690	0.006	0.011	0.002
Average	**5.27**	**4.10**	**0.028**	**0.314**	**6.5**	**0.105**	**0.052**	**0.320**	**2.460**	**0.011**	**0.024**	**0.002**
SD	**0.47**	**0.32**	**0.014**	**0.233**	**2.1**	**0.071**	**0.045**	**0.432**	**3.127**	**0.010**	**0.022**	**0.002**

* pH measured in KCl solution

Table 26.11: *Analytical data obtained from soil samples (0–10 cm) collected on landings, roads and skidder tracks in the Oleolega catchment. LOI in % of oven dry material, exchangeable Na, K, Ca, Mg, NH_4, NO_3 and Ca-Lactate extractable P in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	5.36	4.10	0.137	4.898	11.9	0.113	0.118	1.375	1.071	0.214	0.041	0.012
5	5.12	4.29	0.080	2.716	12.2	0.153	0.214	1.700	2.233	0.069	0.009	0.006
11	5.29	4.36	0.086	2.538	9.5	0.123	0.129	0.905	3.486	0.057	0.069	0.003
18	5.13	3.90	0.027	0.700	6.4	0.136	0.087	0.417	1.556	0.027	0.010	0.001
19	5.54	4.84	0.093	2.082	8.3	0.123	0.247	1.763	1.573	0.141	0.069	0.039
22	5.59	4.20	0.024	0.921	4.8	0.245	0.064	0.391	8.430	0.023	0.031	0.003
24	4.70	3.85	0.055	1.520	7.8	0.219	0.085	0.195	1.205	0.146	0.047	0.009
27	4.75	3.83	0.070	1.979	11.2	0.174	0.138	1.329	1.384	0.078	0.027	0.009
42	4.89	4.32	0.095	2.161	11.2	0.072	0.081	1.954	1.829	0.094	0.081	0.005
45	5.21	4.05	0.064	1.345	5.2	0.200	0.155	0.899	4.047	0.046	0.027	0.009
54	4.88	3.92	0.015	0.363	7.4	0.074	0.054	0.158	0.396	0.024	0.003	0.001
61	5.21	4.38	0.098	3.071	11.7	0.152	0.314	2.131	4.140	0.142	0.096	0.008
64	5.11	4.36	0.099	2.954	15.0	0.162	0.251	3.046	2.444	0.151	0.010	0.004
67	5.22	4.29	0.169	2.943	12.0	0.112	0.280	2.271	3.287	0.141	0.018	0.002
Average	**5.14**	**4.19**	**0.079**	**2.156**	**9.6**	**0.147**	**0.158**	**1.324**	**2.649**	**0.097**	**0.039**	**0.008**
SD	**0.26**	**0.27**	**0.041**	**1.135**	**2.9**	**0.049**	**0.084**	**0.842**	**1.949**	**0.057**	**0.029**	**0.009**

* pH measured in KCl solution

Table 26.12: *Analytical data obtained from soil samples (10–20 cm) collected on landings, roads and skidder tracks in Oleolega catchment. LOI in % of oven dry material, exchangeable Na, K, Ca, Mg, NH_4, NO_3 and Ca-Lactate extractable P in meq 100 g^{-1} dry soil.*

Sample pt.	pH	pH*	%N	%C	LOI	Na	K	Ca	Mg	NH4	NO3	PO4
4	5.28	4.09	0.081	2.633	8.4	0.079	0.063	0.478	0.516	0.053	0.015	0.010
5	5.20	4.18	0.058	1.694	10.5	0.087	0.225	0.890	1.300	0.104	0.008	0.003
11	5.37	4.17	0.042	1.141	8.5	0.136	0.069	0.578	3.103	0.042	0.050	0.001
18	5.17	3.97	0.021	0.505	7.0	0.119	0.080	0.318	2.277	0.019	0.018	0.001
19	5.28	4.03	0.071	1.519	8.3	0.136	0.264	1.521	1.563	0.111	0.074	0.032
22	5.58	4.20	0.045	1.697	5.8	0.195	0.057	0.869	4.185	0.068	0.015	0.008
24	4.65	3.89	0.030	0.851	6.7	0.107	0.047	0.085	0.824	0.069	0.054	0.002
27	4.89	3.84	0.040	0.959	9.5	0.093	0.043	0.490	0.709	0.033	0.010	0.001
42	5.54	4.31	0.052	1.139	9.4	0.054	0.057	1.184	1.125	0.076	0.046	0.005
45	5.07	4.10	0.206	4.162	15.3	0.205	0.233	1.656	4.722	0.122	0.028	0.031
54	4.86	3.93	0.012	0.234	7.0	0.054	0.049	0.093	0.323	0.024	0.004	0.001
61	5.36	4.38	0.073	2.147	9.7	0.123	0.229	1.876	3.960	0.102	0.052	0.005
64	4.90	4.14	0.058	1.387	10.8	0.068	0.083	0.592	0.792	0.047	0.043	0.001
67	5.19	4.18	0.120	1.846	10.2	0.097	0.161	1.414	2.524	0.066	0.003	0.002
Average	**5.17**	**4.10**	**0.065**	**1.565**	**9.1**	**0.111**	**0.119**	**0.860**	**1.995**	**0.067**	**0.030**	**0.007**
SD	**0.26**	**0.15**	**0.047**	**0.945**	**2.3**	**0.045**	**0.081**	**0.563**	**1.428**	**0.032**	**0.022**	**0.010**

* pH measured in KCl solution

Table 26.13: *Analytical data obtained from soil samples (30–60 cm) collected on landings, roads and skidder tracks in Oleolega catchment. LOI in % of oven dry material.*

Sample pt.	pH	pH*	%N	%C	LOI
4	5.46	4.13	0.021	0.336	4.7
5	5.09	3.95	0.028	0.468	13.1
11	5.50	4.08	0.019	0.245	7.1
18	5.62	4.01	0.048	0.055	7.4
19	5.16	4.37	0.012	0.163	4.6
22	6.50	3.64	0.008	0.111	3.1
24	4.77	3.88	0.003	0.064	4.9
27	4.99	3.83	0.017	0.268	8.5
42	5.14	4.21	0.038	0.807	8.6
45	6.34	4.02	0.019	0.108	7.7
54	4.81	3.96	0.007	0.091	6.4
61	5.36	4.12	0.036	0.861	9.1
64	5.06	4.10	0.031	0.130	10.2
67	5.23	4.16	0.038	0.293	6.8
Average	**5.36**	**4.03**	**0.023**	**0.286**	**7.3**
SD	**0.49**	**0.17**	**0.013**	**0.251**	**2.5**

* pH measured in KCl solution

Chapter 27

Analytical Data of the Vegetation

The concentrations of nutrients in mission grass and in pine components sampled during the biomass study are given in this appendix. Nutrient concentrations in mission grass, sampled in February 1991, are given in Table 27.1.

Table 27.1: *Nutrient concentrations in mission grass (Pennisetum polystachyon) sampled in the grassland plot adjacent to the Nabou Forest Estate headquarters. Macronutrients are in % of dry weight, micronutrients in ppm.*

Code	N	P	K	Ca	Mg	Zn	Mn	B
GRS1	0.471	0.036	1.127	0.178	0.202			
GRS2	0.466	0.049	1.529	0.267	0.279	15	284	3.9

The macronutrient (N, P, K, Ca and Mg) concentrations observed in pine components are shown in Tables 27.2, 27.3, 27.4, 27.5 and Table 27.6 respectively. Separate foliage samples were collected from the lower 2–3 m of the crown (low), the middle 2–3 m of the crown (mid) and the upper 2–3 m of the crown (high). Concentrations of Zn, Mn and B in the foliage are given in Table 27.8.

Concentrations of nutrients in tree stems sampled in the Oleolega catchment in December 1990 (O1–O12) and in march 1991 (O13, O14) are given in Table 27.7. Samples coded O1, O2 and O3 were collected at sample point A (see Figure 15.3, Chapter 4), samples O4, O5, and O6 at sample point B, samples O7, O8, and O9 at sample point C, O10, O11 and O12 at sample point D and samples O13 and O14 were collected at sample point E.

Table 27.2: *Nitrogen concentrations (% of dry weight) in components of Pinus caribaea in Nabou Forest Estate.*

Tree Code	Stem Wood	Stem Bark	Dead Branches	Dead Twigs	Live Branches	Live Twigs	Dead Needles	Live Needles Low	Live Needles Mid	Live Needles High
A32	0.068	0.158	0.090	0.124	0.173	0.384	0.325	0.994	0.985	1.154
A47	0.088	0.167	0.072	0.101	0.204	0.330		0.624	0.818	0.792
A126	0.068	0.109	0.056	0.121	0.136	0.415	0.320	0.845	0.869	0.896
A141	0.129	0.287	0.100	0.182	0.196	0.296		0.873	0.891	1.051
A221	0.121	0.185	0.094	0.161	0.179	0.438	0.272	0.824	0.920	1.082
B17	0.103	0.162	0.089	0.148	0.174	0.455	0.564	0.873	0.981	1.006
B32	0.048	0.139	0.073	0.134	0.091	0.454	0.440	0.890	0.988	1.030
B59	0.072	0.207	0.087	0.161	0.140	0.892	0.475	0.986	1.112	1.318
B80	0.063	0.130	0.104	0.188	0.136	0.382	0.534	0.896	0.954	1.025
B92	0.076	0.141	0.076	0.149	0.162	0.359	0.444	0.765	0.865	0.892
C20	0.061	0.106	0.089	0.153	0.157	0.404	0.491	0.953	1.014	1.071
C88	0.089	0.199	0.150	0.157	0.130	0.460	0.378	0.925	0.913	1.071
C98	0.052	0.161	0.096	0.130	0.108	0.433	0.364	1.017	1.029	1.051
O13	0.092	0.215	0.100	0.167	0.137	0.492		1.226	1.205	1.308
O14	0.073	0.174	0.083	0.144	0.138	0.388		0.966	0.974	0.965

A=Tulasewa forest; B=Korokula forest; C=Koromani forest; O=Oleolega catchment

Table 27.3: *Phosphorus concentrations (% of dry weight) in components of Pinus caribaea in Nabou Forest Estate.*

Tree Code	Stem Wood	Stem Bark	Dead Branches	Dead Twigs	Live Branches	Live Twigs	Dead Needles	Live Needles Low	Live Needles Mid	Live Needles High
A32	0.013	0.020	0.005	0.010	0.029	0.070	0.016	0.077	0.077	0.095
A47	0.014	0.010	0.009	0.009	0.023	0.109		0.072	0.095	0.134
A126	0.015	0.021	0.008	0.016	0.034	0.118	0.032	0.095	0.123	0.135
A141	0.015	0.029	0.007	0.009	0.022	0.037		0.067	0.071	0.080
A221	0.016	0.020	0.008	0.012	0.029	0.111	0.023	0.081	0.095	0.116
B17	0.008	0.102	0.050	0.052	0.013	0.065	0.031	0.066	0.068	0.063
B32	0.007	0.011	0.005	0.005	0.027	0.059	0.026	0.056	0.070	0.081
B59	0.031	0.035	0.007	0.010	0.018	0.163	0.025	0.079	0.074	0.079
B80	0.012	0.166	0.010	0.015	0.018	0.061	0.043	0.067	0.066	0.070
B92	0.023	0.032	0.006	0.018	0.019	0.054	0.028	0.057	0.068	0.071
C20	0.006	0.004	0.003	0.008	0.021	0.061	0.027	0.075	0.069	0.074
C88	0.010	0.013	0.015	0.009	0.018	0.066	0.016	0.065	0.061	0.064
C98	0.006	0.018	0.006	0.008	0.011	0.063	0.044	0.069	0.082	0.103
O13	0.012	0.018	0.007	0.010	0.012	0.052		0.069	0.071	0.085
O14	0.014	0.019	0.007	0.009	0.014	0.047		0.054	0.053	0.060

A=Tulasewa forest; B=Korokula forest; C=Koromani forest; O=Oleolega catchment

Table 27.4: *Potassium concentrations (% of dry weight) in components of Pinus caribaea in Nabou Forest Estate.*

Tree Code	Stem Wood	Stem Bark	Dead Branches	Dead Twigs	Live Branches	Live Twigs	Dead Needles	Live Needles Low	Live Needles Mid	Live Needles High
A32	0.050	0.099	0.018	0.015	0.142	0.375	0.113	0.467	0.478	0.570
A47	0.065	0.079	0.025	0.020	0.148	0.383		0.272	0.323	0.465
A126	0.061	0.092	0.022	0.042	0.126	0.396	0.125	0.417	0.526	0.794
A141	0.064	0.139	0.022	0.018	0.132	0.219		0.339	0.376	0.479
A221	0.097	0.081	0.050	0.066	0.182	0.461	0.085	0.425	0.421	0.660
B17	0.040	0.048	0.025	0.020	0.078	0.320	0.078	0.421	0.393	0.452
B32	0.031	0.052	0.023	0.026	0.054	0.232	0.056	0.210	0.209	0.230
B59	0.046	0.055	0.015	0.023	0.085	0.504	0.070	0.324	0.349	0.543
B80	0.033	0.028	0.028	0.031	0.073	0.258	0.123	0.368	0.327	0.279
B92	0.047	0.072	0.020	0.025	0.093	0.276	0.081	0.378	0.338	0.328
C20	0.042	0.040	0.033	0.025	0.085	0.300	0.088	0.380	0.309	0.499
C88	0.046	0.039	0.041	0.021	0.073	0.235	0.082	0.341	0.348	0.398
C98	0.045	0.109	0.048	0.061	0.111	0.416	0.116	0.457	0.529	1.075
O13	0.052	0.123	0.036	0.027	0.085	0.350		0.362	0.370	0.573
O14	0.062	0.130	0.036	0.057	0.132	0.434		0.484	0.503	0.792

A=Tulasewa forest; B=Korokula forest; C=Koromani forest; O=Oleolega catchment

Table 27.5: *Calcium concentrations (% of dry weight) in components of Pinus caribaea in Nabou Forest Estate.*

Tree Code	Stem Wood	Stem Bark	Dead Branches	Dead Twigs	Live Branches	Live Twigs	Dead Needles	Live Needles Low	Live Needles Mid	Live Needles High
A32	0.046	0.042	0.128	0.153	0.109	0.180	0.966	0.701	0.473	0.318
A47	0.047	0.041	0.131	0.168	0.108	0.143		0.825	0.517	0.294
A126	0.054	0.059	0.166	0.213	0.111	0.185	0.544	0.502	0.314	0.130
A141	0.042	0.065	0.151	0.198	0.139	0.198		0.769	0.716	0.438
A221	0.049	0.052	0.143	0.196	0.100	0.186	0.686	0.699	0.569	0.282
B17	0.044	0.038	0.089	0.141	0.079	0.123	0.490	0.353	0.304	0.220
B32	0.064	0.068	0.122	0.256	0.115	0.233	0.952	1.009	0.662	0.361
B59	0.046	0.067	0.145	0.233	0.104	0.373	0.626	0.665	0.460	0.264
B80	0.050	0.056	0.134	0.275	0.134	0.197	0.514	0.347	0.353	0.297
B92	0.055	0.137	0.199	0.275	0.167	0.231	0.630	0.391	0.334	0.229
C20	0.062	0.058	0.159	0.271	0.166	0.281	0.757	0.572	0.533	0.345
C88	0.074	0.125	0.141	0.286	0.144	0.298	0.713	0.598	0.471	0.300
C98	0.069	0.206	0.239	0.392	0.205	0.495	0.813	0.929	0.711	0.319
O13	0.044	0.064	0.135	0.266	0.118	0.281		0.789	0.732	0.482
O14	0.058	0.116	0.124	0.239	0.139	0.243		0.562	0.443	0.209

A=Tulasewa forest; B=Korokula forest; C=Koromani forest; O=Oleolega catchment

Table 27.6: *Magnesium concentrations (% of dry weight) in components of Pinus caribaea in Nabou Forest Estate.*

Tree Code	Stem Wood	Stem Bark	Dead Branches	Dead Twigs	Live Branches	Live Twigs	Dead Needles	Live Needles Low	Live Needles Mid	Live Needles High
A32	0.019	0.041	0.055	0.082	0.070	0.118	0.277	0.269	0.227	0.206
A47	0.027	0.037	0.061	0.103	0.094	0.142		0.275	0.218	0.209
A126	0.024	0.032	0.045	0.075	0.061	0.124	0.149	0.146	0.152	0.145
A141	0.018	0.045	0.040	0.083	0.062	0.111		0.226	0.226	0.200
A221	0.021	0.043	0.038	0.073	0.050	0.105	0.229	0.250	0.227	0.164
B17	0.026	0.042	0.047	0.074	0.061	0.126	0.295	0.230	0.246	0.268
B32	0.022	0.045	0.036	0.073	0.046	0.130	0.202	0.363	0.251	0.195
B59	0.025	0.068	0.060	0.113	0.075	0.365	0.402	0.424	0.416	0.381
B80	0.026	0.040	0.050	0.091	0.068	0.140	0.371	0.268	0.288	0.295
B92	0.020	0.040	0.041	0.075	0.059	0.117	0.255	0.195	0.214	0.231
C20	0.022	0.023	0.029	0.045	0.039	0.078	0.210	0.161	0.175	0.181
C88	0.024	0.029	0.039	0.069	0.052	0.121	0.195	0.185	0.145	0.136
C98	0.019	0.058	0.038	0.062	0.043	0.142	0.128	0.184	0.151	0.163
O13	0.016	0.047	0.033	0.061	0.052	0.156		0.213	0.231	0.220
O14	0.020	0.031	0.028	0.055	0.043	0.119		0.124	0.110	0.107

A=Tulasewa forest; B=Korokula forest; C=Koromani forest; O=Oleolega catchment

Table 27.7: *Nutrient concentrations in Pinus caribaea stems (wood and bark) sampled at several locations in the Oleolega catchment.*

Code	N	P	K	Ca	Mg	Zn	Mn	B	Dbhob	h
O1	0.072	0.018	0.053	0.041	0.021	5	36	2.1	0.352	20.1
O2	0.066	0.009	0.041	0.043	0.024	6	60	1.0	0.253	18.7
O3	0.092	0.012	0.056	0.037	0.019	28	45	1.1	0.250	19.4
O4	0.072	0.008	0.046	0.033	0.021	18	30	1.1	0.240	18.8
O5	0.082	0.008	0.054	0.033	0.020	8	70	1.3	0.256	19.0
O6	0.071	0.006	0.050	0.027	0.021	13	17	1.0	0.243	18.0
O7	0.078	0.007	0.046	0.061	0.024	13	79	1.4	0.282	17.1
O8	0.079	0.006	0.045	0.062	0.018	9	35	0.9	0.252	19.3
O9	0.075	0.006	0.042	0.041	0.021	12	32	1.1	0.230	19.3
O10	0.085	0.009	0.049	0.039	0.018	3	101	0.7	0.324	17.7
O11	0.109	0.013	0.080	0.033	0.024	8	84	1.1	0.299	20.3
O12	0.079	0.007	0.046	0.041	0.016	5	91	1.2	0.256	19.6
O13	0.107	0.013	0.061	0.046	0.020				0.260	18.7
O14	0.082	0.014	0.068	0.063	0.021				0.264	20.3

Table 27.8: *Concentrations of Zn, Mn and B (ppm) in foliage of Pinus caribaea in Nabou Forest Estate.*

Tree Code	Dead Needles	Live Needles Low	Live Needles Mid	Live Needles High	Dead Needles	Live Needles Low	Live Needles Mid	Live Needles High
	Zn	**Zn**	**Zn**	**Zn**	**B**	**B**	**B**	**B**
A32	31	29	29	26	12.5	10.7	7.9	7.3
A47		35	31	33		9.0	7.0	8.0
A126	23	25	25	15	9.1	7.9	6.5	4.9
A141		42	50	57		14.0	10.0	11.0
A221	36	34	35	28	10.5	10.9	10.7	9.1
B17	12	14	19	24	10.2	10.2	9.8	10.3
B32	35	38	35	32	16.6	15.7	13.1	10.4
B59	23	28	36	49	15.7	15.5	13.9	20.3
B80	28	30	33	35	12.2	9.7	10.0	9.3
B92	18	14	22	29	14.3	11.8	11.0	10.2
C20	26	22	28	33	13.4	12.8	11.8	16.2
C88	22	24	23	24	14.9	13.1	10.6	8.3
C98	29	35	37	39	15.9	21.1	16.2	14.3
O13		32	40	49		15.8	14.5	15.8
O14		34	32	31		17.2	14.9	20.0
	Mn	**Mn**	**Mn**	**Mn**				
A32	1249	987	643	442				
A47		432	743	579				
A126	620	632	405	201				
A141		229	651	573				
A221	533	649	513	254				
B17	274	268	252	194				
B32	414	470	313	219				
B59	368	474	310	187				
B80	328	274	289	234				
B92	399	304	283	220				
C20	273	240	208	160				
C88	516	361	335	228				
C98	670	787	682	296				
O13		2013	2175	1574				
O14		961	734	152				

A=Tulasewa forest; B=Korokula forest; C=Koromani forest; O=Oleolega catchment

Chapter 28

Litter and Litter Fall Data

28.1 Needle fall

Monthly concentrations and amounts of needle fall in Tulasewa, Korokula and Koromani forests are presented in Tables 28.1, 28.2 and 28.3 respectively.

28.2 Needle and Undergrowth Litter

Concentrations of nutrients in needle litter on the forest floor are presented in Table 28.4 for the Tulasewa, Korokula and Koromani forest plots. As the undergrowth litter mass (mainly mission grass) accounted for a large proportion of the total litter layer mass in Tulasewa forest concentrations for this component were determined at a similar frequency as for those of needle litter on the forest floor. To reduce the number of samples in the Tulasewa forest plot, bulk samples were analysed for the periods January–March and April–June 1990.

Table 28.1: *Nutrient concentrations and amounts of needle fall as observed in Tulasewa forest.*

Field Code	Month	N %	P %	K %	Ca %	Mg %	B ppm	Mn ppm	Zn ppm	Amount kg/ha
ALF1	Dec'90	0.364	0.018	0.152	0.922	0.228	12	486	27	366.8
ALF2	Jan'90	0.401	0.015	0.095	0.863	0.203	10	490	28	525.8
ALF3	Feb'90	0.380	0.017	0.082	0.840	0.188	9	608	30	163.7
ALF4	Mar'90	0.395	0.013	0.074	0.862	0.195	9	498	26	773.0
ALF5	Apr'90	0.467	0.024	0.099	0.923	0.198	9	697	32	250.7
ALF6	May'90	0.431	0.019	0.125	0.855	0.193	9	647	26	264.0
ALF7	Jun'90	0.389	0.020	0.092	1.029	0.187	9	634	28	678.4
ALF8	Jul'90	0.391	0.014	0.096	0.928	0.190	9	602	25	271.7
ALF9	Aug'90	0.381	0.011	0.075	0.811	0.204	9	512	24	614.1
ALF10	Sep'90	0.357	0.010	0.061	0.833	0.199	9	605	23	343.5
ALF11	Oct'90	0.305	0.018	0.101	0.796	0.219	10.1	614	23	189.7
ALF12	Nov'90*	0.672	0.071	0.323	0.625	0.196	8.0	498	24	6219.8
ALF13	Dec'90*	0.652	0.055	0.230	0.467	0.168	8.0	382	27	655.1
ALF14	Jan'91	0.663	0.055	0.181	0.737	0.201	8.7	509	37	352.7
ALF15	Feb'91	0.591	0.047	0.155	0.748	0.212	8.8	515	31	177.7
ALF16	Mar'91	0.477	0.041	0.105	0.885	0.235	10.2	618	31	211.4
ALF17	Apr'91	0.402	0.030	0.082	0.974	0.239	11.1	650	30	226.7
ALF18	May'91	0.409	0.027	0.110	0.803	0.234	9.9	699	30	345.3
ALF19	Jun'91	0.390	0.025	0.083	0.832	0.214	10.1	642	27	281.8
ALF20	Jul'91	0.319	0.024	0.084	0.866	0.251	11.0	696	29	257.4
ALF21	Aug'91	0.366	0.027	0.087	0.830	0.220	10.5	721	29	527.4
ALF22	Sep'91	0.375	0.043	0.075	0.777	0.214	10.4	678	27	296.3

*: Litter fall resulting from cyclone Sina

Table 28.2: *Nutrient concentrations and amounts of needle fall as observed in Korokula forest.*

Field Code	Month	N %	P %	K %	Ca %	Mg %	B ppm	Mn ppm	Zn ppm	Amount kg/ha
BLF1	Jan'90	0.290	0.012	0.033	0.894	0.330	13.2	433	12	663.3
BLF2	Feb'90	0.313	0.012	0.100	0.734	0.311	12.2	374	14	132.5
BLF3	Mar'90	0.422	0.021	0.115	0.678	0.295	13.4	300	12	859.2
BLF4	Apr'90	0.323	0.013	0.080	0.756	0.348	12.1	366	11	395.2
BLF5	May'90	0.264	0.006	0.077	0.786	0.357	13.9	358	17	1746.4
BLF6	Jun'90	0.285	0.008	0.057	0.785	0.313	13.6	444	12	448.7
BLF7	Jul'90	0.300	0.010	0.069	0.762	0.317	13.2	388	12	457.1
BLF8	Aug'90	0.314	0.009	0.060	0.878	0.308	14.9	455	13	343.8
BLF9	Sep'90	0.362	0.013	0.069	0.859	0.300	17.9	392	16	181.4
BLF10	Oct'90	0.341	0.027	0.063	0.707	0.288	13.2	409	18	328.2
BLF11	Nov'90*	0.764	0.049	0.233	0.561	0.311	15.1	382	15	9187.5
BLF21	Dec'90*	0.885	0.045	0.119	0.571	0.279	12.4	355	23	634.2
BLF12	Jan'91	0.725	0.092	0.092	0.606	0.325	14.9	399	27	430.4
BLF13	Feb'91	0.594	0.104	0.101	0.679	0.321	14.6	428	25	244.0
BLF14	Mar'91	0.595	0.054	0.082	0.712	0.340	14.9	446	22	240.4
BLF15	Apr'91	0.441	0.044	0.065	0.733	0.338	14.0	226	20	281.3
BLF16	May'91	0.485	0.112	0.108	0.711	0.367	13.9	220	18	524.2
BLF17	Jun'91	0.337	0.132	0.080	0.762	0.346	14.1	508	19	291.3
BLF18	Jul'91	0.375	0.137	0.074	0.696	0.356	15.1	493	19	237.1
BLF19	Aug'91	0.337	0.124	0.070	0.658	0.330	15.0	413	20	396.4
BLF20	Sep'91	0.353	0.020	0.063	0.693	0.323	13.4	464	20	190.7

*: Litter fall resulting from cyclone Sina

Table 28.3: *Nutrient concentrations and amounts of needle fall as observed in Koromani forest.*

Field Code	Month	N %	P %	K %	Ca %	Mg %	B ppm	Mn ppm	Zn ppm	Amount kg/ha
CLF1	Feb'90	0.273	0.014	0.070	0.788	0.214	12	707	18	124.6
CLF2	Mar'90	0.404	0.013	0.106	0.699	0.206	11	565	15	864.7
CLF3	Apr'90	0.379	0.009	0.111	0.724	0.238	11	712	16	381.7
CLF4	May'90	0.282	0.010	0.107	0.672	0.219	9	655	15	732.4
CLF5	Jun'90	0.320	0.009	0.073	0.678	0.215	10	533	13	379.2
CLF6	Jul'90	0.299	0.007	0.106	0.678	0.185	10	626	14	212.3
CLF7	Aug'90	0.336	0.010	0.093	0.652	0.181	8	524	16	455.1
CLF8	Sep'90	0.378	0.013	0.093	0.655	0.176	15	659	45	155.5
CLF9	Oct'90	0.335	0.012	0.098	0.597	0.173	10	637	16	130.1
CLF10	Nov'90*	0.831	0.050	0.288	0.522	0.188	11	590	21	6018.3
CLF11	Dec'90*	0.664	0.034	0.150	0.491	0.161	10	744	23	994.0
CLF12	Jan'91	0.624	0.027	0.147	0.667	0.186	9.2	590	22	530.9
CLF13	Feb'91	0.673	0.032	0.127	0.605	0.185	11.9	721	42	234.1
CLF14	Mar'91	0.691	0.033	0.117	0.583	0.193	10.8	703	21	293.7
CLF15	Apr'91	0.514	0.019	0.101	0.677	0.187	11.5	778	23	297.5
CLF16	May'91	0.474	0.020	0.106	0.676	0.187	12.2	824	22	362.3
CLF17	Jun'91	0.418	0.018	0.097	0.698	0.192	13.6	789	23	233.4
CLF18	Jul'91	0.397	0.011	0.090	0.688	0.172	11.8	781	25	247.3
CLF19	Aug'91	0.365	0.010	0.078	0.663	0.179	11.8	792	26	311.8
CLF20	Sep'91	0.398	0.013	0.083	0.646	0.173	11.2	756	24	167.8

*: Litter fall resulting from cyclone Sina

Table 28.4: *Nutrient concentrations and amounts of needle and undergrowth litter on the forest floors in the Tulasewa, Korokula and Koromani forest plots.*

Date	**N** %	**P** %	**K** %	**Ca** %	**Mg** %	**B** ppm	**Mn** ppm	**Zn** ppm	**Amount** kg/ha
TULASEWA FOREST, Planted 1984									
Needle Litter									
14-Jan-90				Bulked					3057.5
15-Feb-90				Bulked					1250.2
15-Mar-90	0.415	0.020	0.056	0.868	0.210	10.0	541	28.5	2302.5
15-Apr-90				Bulked					2100.9
16-May-90				Bulked					3002.1
19-Jun-90	0.393	0.018	0.076	0.940	0.203	8.5	639	33.5	5450.8
18-Sep-90	0.442	0.022	0.083	0.888	0.248	10.5	730	33.5	3496.0
08-Jan-91	0.829	0.057	0.184	0.792	0.205	9.4	643	31.5	9090.7
02-Apr-91	0.864	0.051	0.068	0.795	0.212	8.5	657	32.1	6981.4
30-Jul-91	0.937	0.061	0.170	0.794	0.222	9.7	739	32.7	6238.0
Undergrowth Litter									
14-Jan-90			Bulked						6660.0
15-Feb-90			Bulked						6445.4
15-Mar-90	0.526	0.024	0.110	0.193	0.148				7877.8
15-Apr-90			Bulked						5199.7
16-May-90			Bulked						6738.3
19-Jun-90	0.528	0.027	0.109	0.271	0.158				5546.3
18-Sep-90	0.535	0.026	0.126	0.250	0.183				7438.9
08-Jan-91	0.711	0.040	0.099	0.412	0.198				8172.2
02-Apr-91	0.959	0.054	0.110	0.618	0.244				5051.2
30-Jul-91	0.901	0.058	0.185	0.710	0.267				4591.3
KOROKULA FOREST, Planted 1979									
Needle Litter									
15-Jan-90	0.540	0.027	0.050	0.766	0.295	13.5	410	16	8888.2
14-Feb-90	0.450	0.025	0.044	0.677	0.282	11.1	427	16	9929.5
16-Mar-90	0.466	0.023	0.043	0.732	0.295	10.1	421	16	8806.0
16-Apr-90	0.496	0.019	0.056	0.770	0.282	13.5	454	12	7510.4
16-May-90	0.453	0.015	0.049	0.799	0.298	13.6	455	13	9906.7
18-Jun-90	0.512	0.020	0.053	0.749	0.298	15.2	487	15	11033.4
18-Sep-90	0.431	0.018	0.046	0.849	0.335	10.5	444	11.5	7138.8
09-Jan-91	0.666	0.034	0.104	0.707	0.304	11.9	414	17.7	14855.6
08-Apr-91	0.815	0.038	0.078	0.748	0.236	10.9	448	20.9	9473.1
02-Aug-91	0.868	0.038	0.081	0.739	0.315	11.3	473	23.0	10288.5
KOROMANI FOREST, Planted 1975									
Needle Litter									
15-Jan-90	0.415	0.014	0.070	0.788	0.214	12	707	18	8231.9
14-Feb-90	0.370	0.013	0.106	0.699	0.206	11	565	15	7515.5
15-Mar-90	0.459	0.009	0.111	0.724	0.238	11	712	16	7217.0
16-Apr-90	0.506	0.010	0.107	0.672	0.219	9	655	15	7959.1
16-May-90	0.369	0.009	0.073	0.678	0.215	10	533	13	10678.9
18-Jun-90	0.428	0.007	0.106	0.678	0.185	10	626	14	9130.8
17-Sep-90	0.490	0.014	0.073	0.722	0.191	8.3	626	18.1	8307.2
07-Jan-91	0.717	0.042	0.149	0.706	0.208	12.6	758	21.0	13464.3
01-Apr-91	0.840	0.047	0.072	0.694	0.210	10.3	807	22.4	10441.0
02-Aug-91	0.848	0.049	0.086	0.716	0.228	11.7	727	22.5	8706.2